QCD spectrometer and arrays
Progress Report

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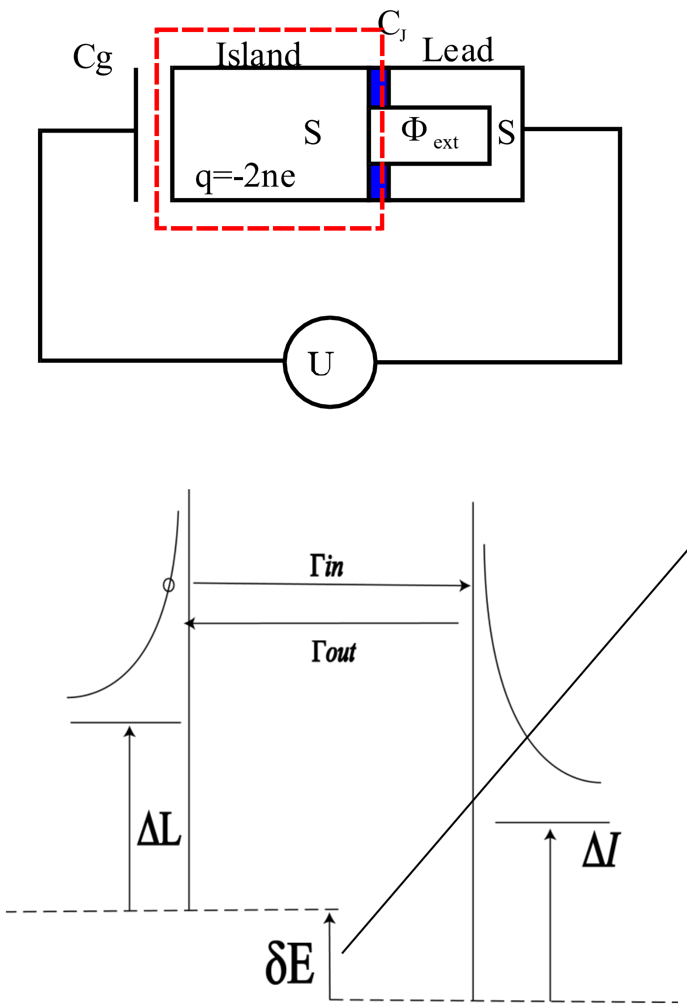
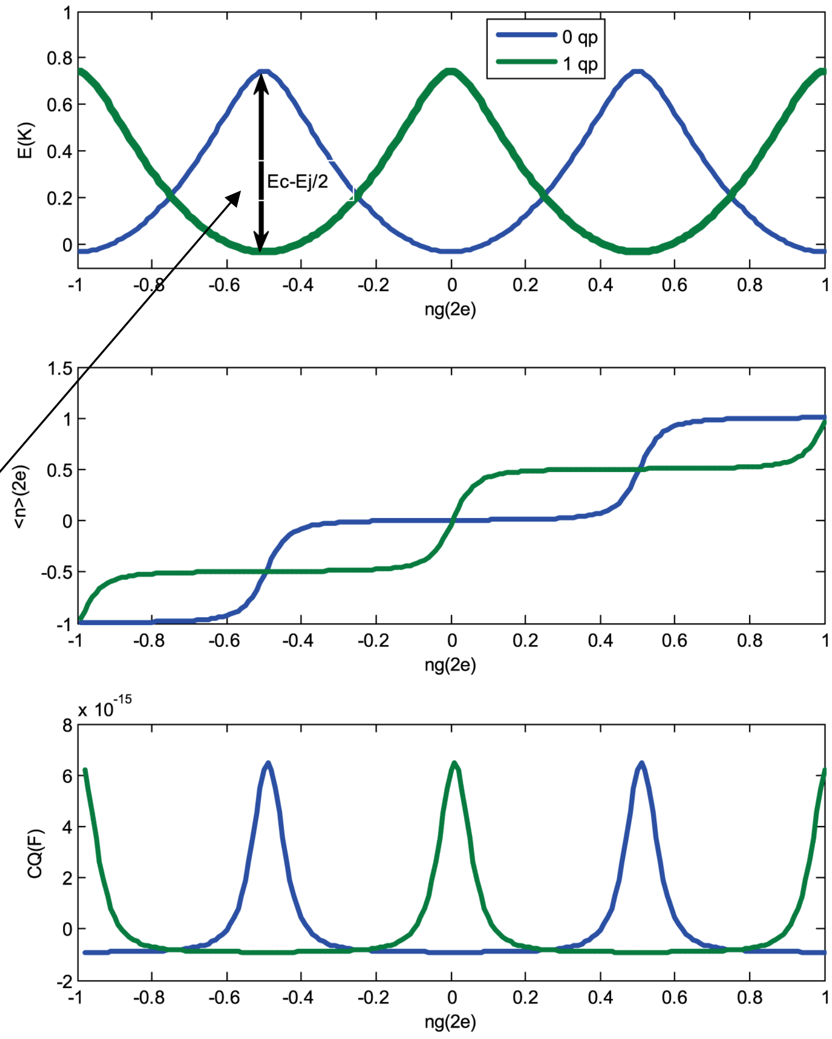
Multiplexed readout – Lorenzo Minutolo and Roger O’Brient

Electron Beam Lithography by Richard E.Muller
Fresnel lens array by Daniel Wilson

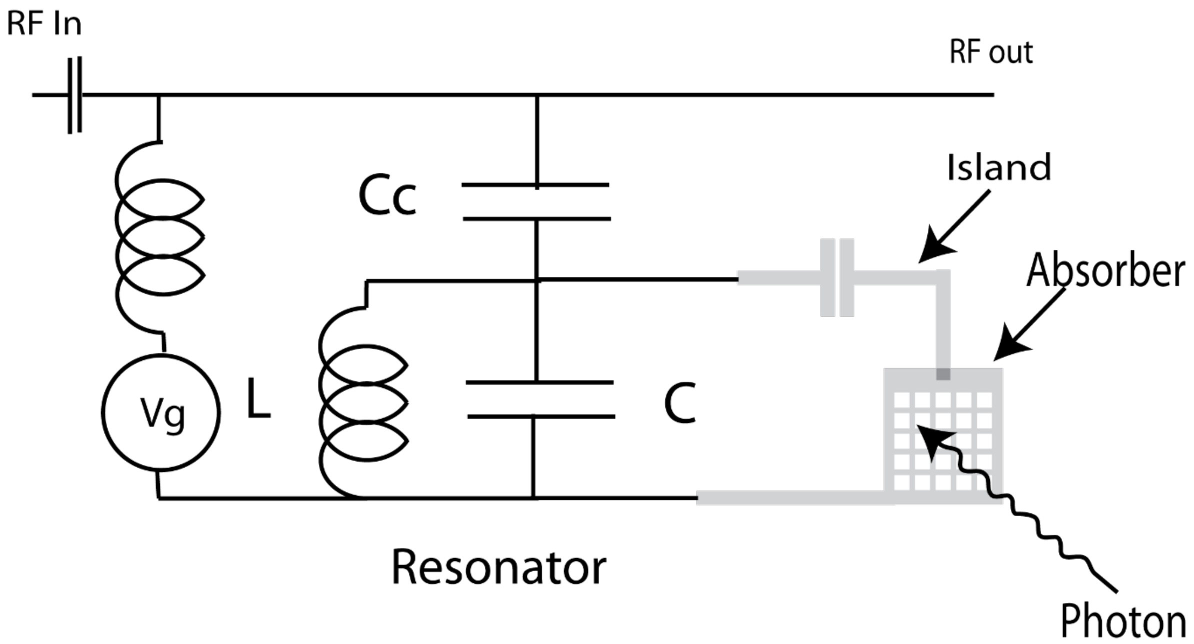
This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

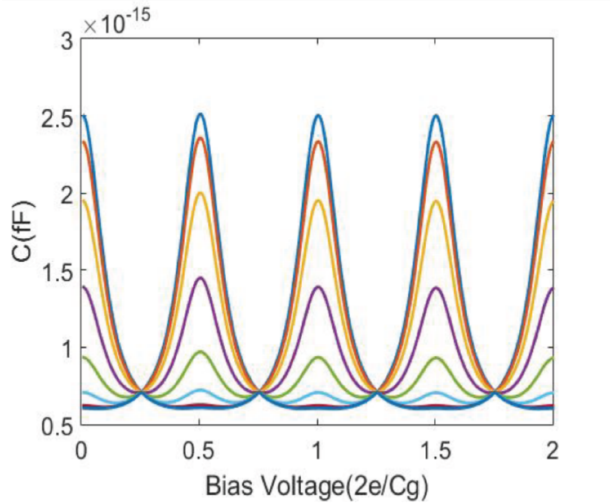
Single Cooper-pair Box (SCB)

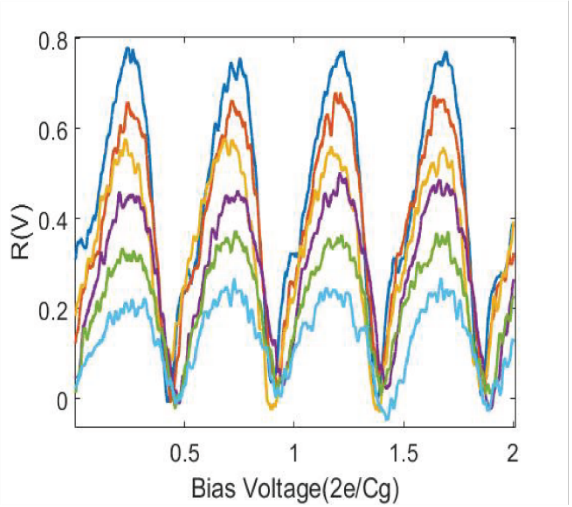




Quantum Capacitance Detector

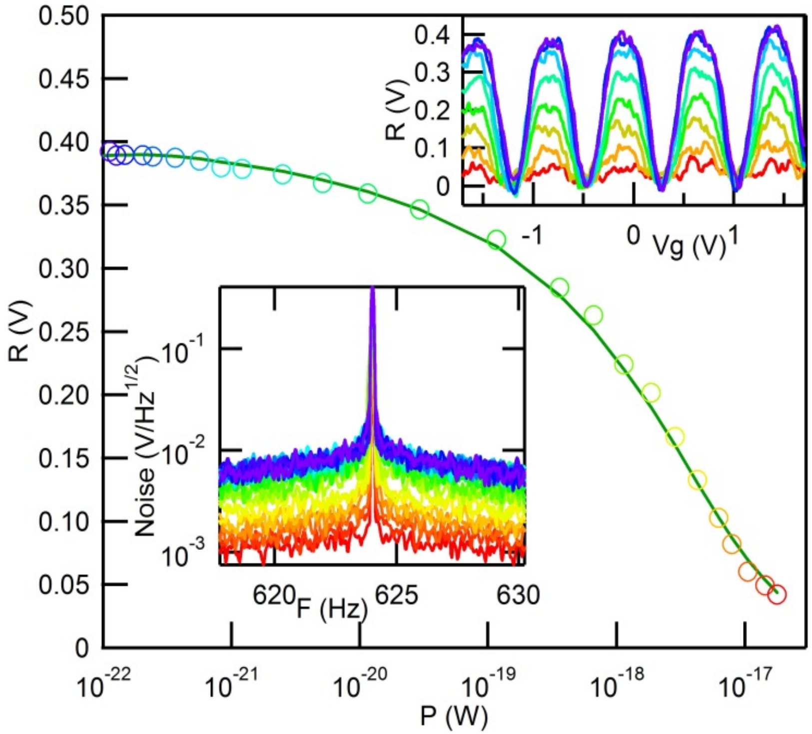






The Quantum Capacitance Detector

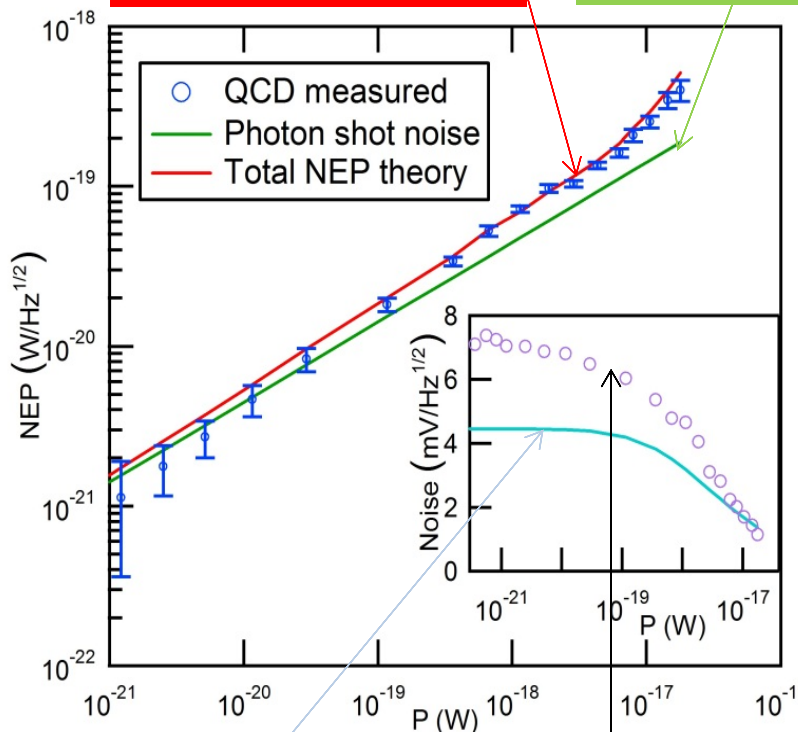
Response and noise as a function of optical signal



NEP as a function of optical signal
Photon shot noise limited!

$$NEP_{tot} = \sqrt{NEP_{ph}^2 + NEP_{sn}^2}$$

$$NEP_{ph} = \sqrt{2h\nu P_s}$$



Shot noise of electron tunneling

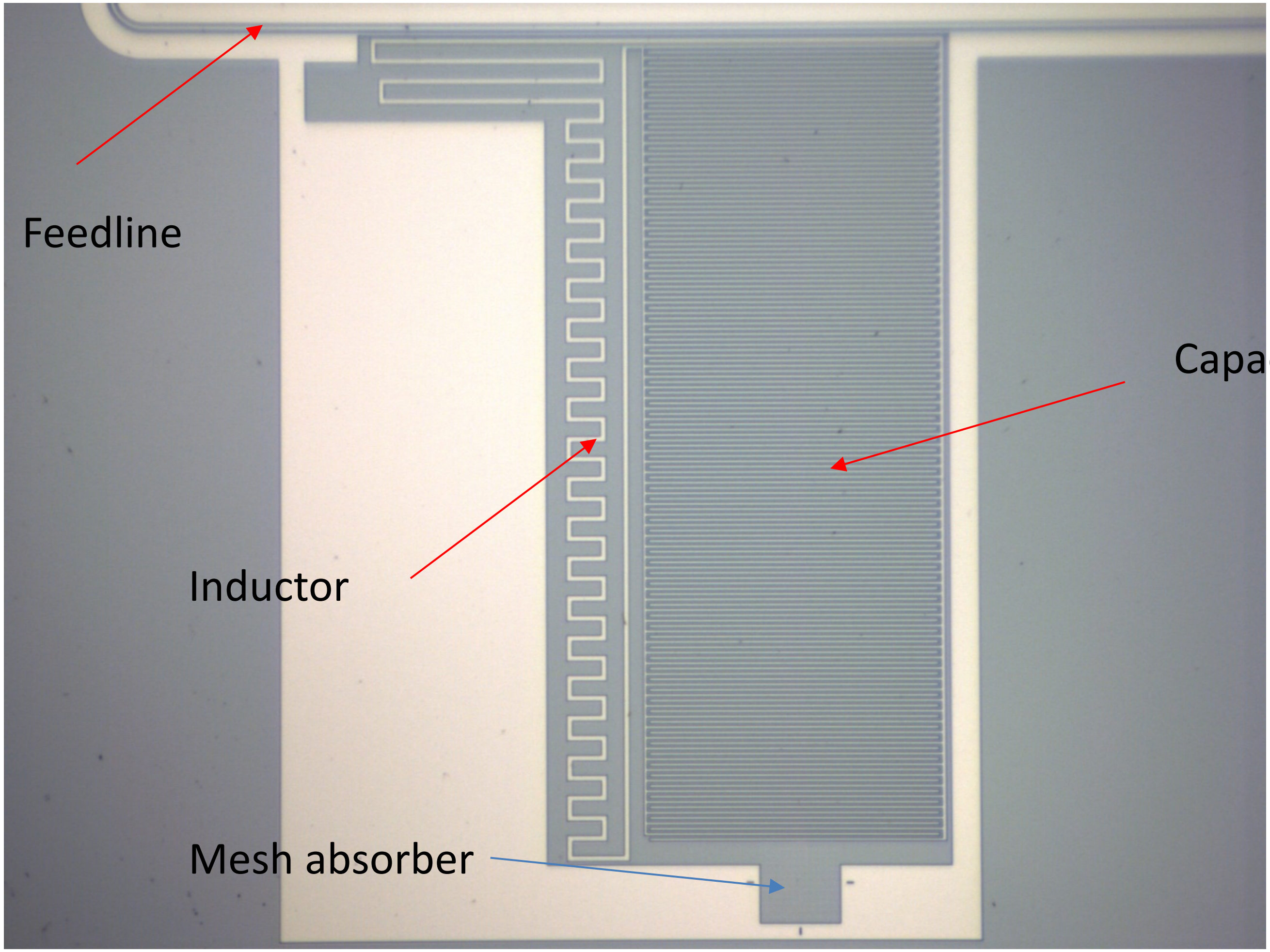
$$S_{sn}(f) = \sqrt{2A^2(\Gamma_{in}\Gamma_{out} / \Gamma_{\Sigma}) / (\Gamma_{\Sigma}^2 + (2\pi f)^2)}$$

Total measured noise

$$NEP_{SN} = S_{SN}(f)/(\frac{dR}{dP})$$

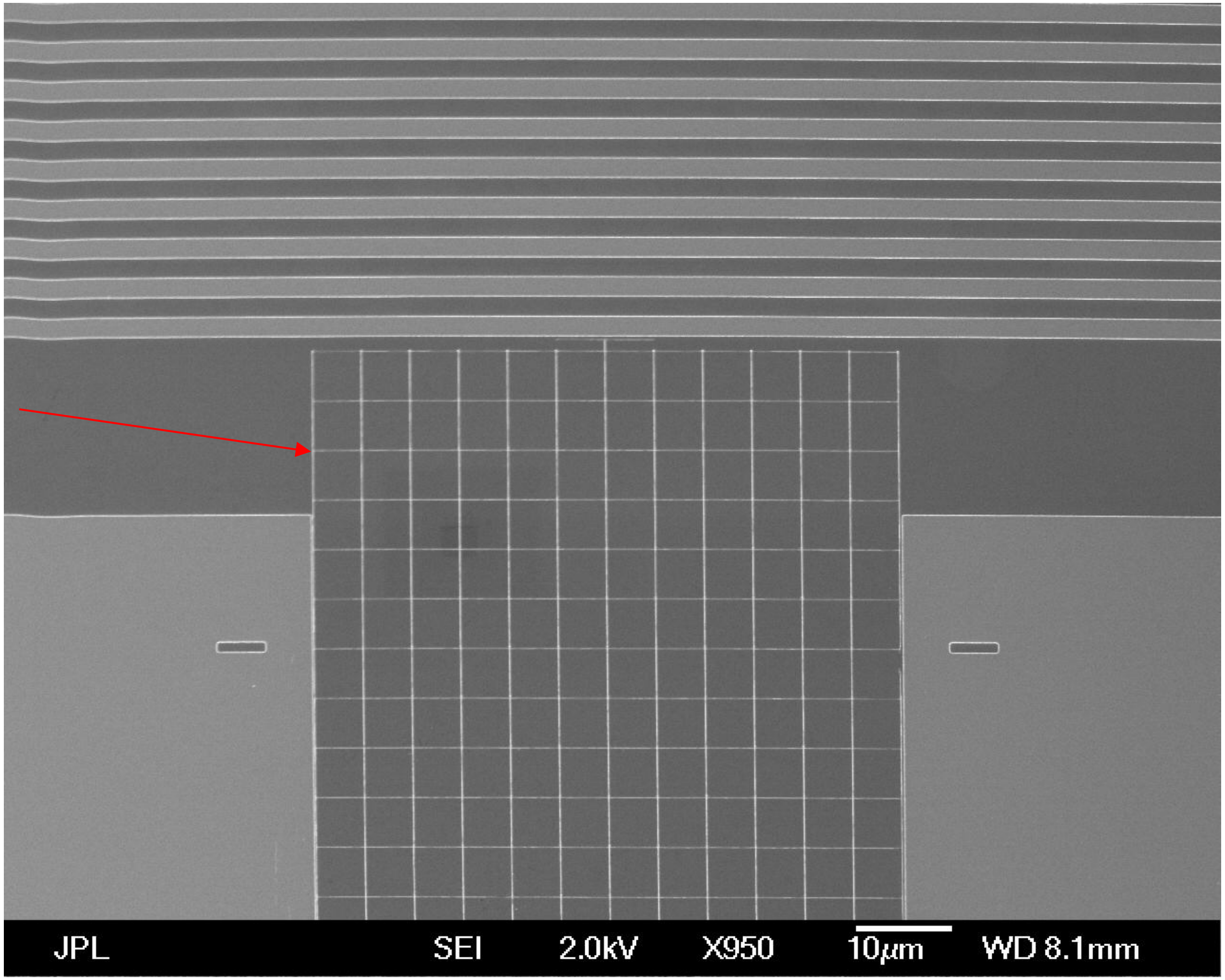
Lens coupled mesh absorber LEQCD

- Need mesh absorber instead of antenna to better couple to spectrometer modes
- Lumped element resonator saves space and has better characteristics than CPW half wave resonator

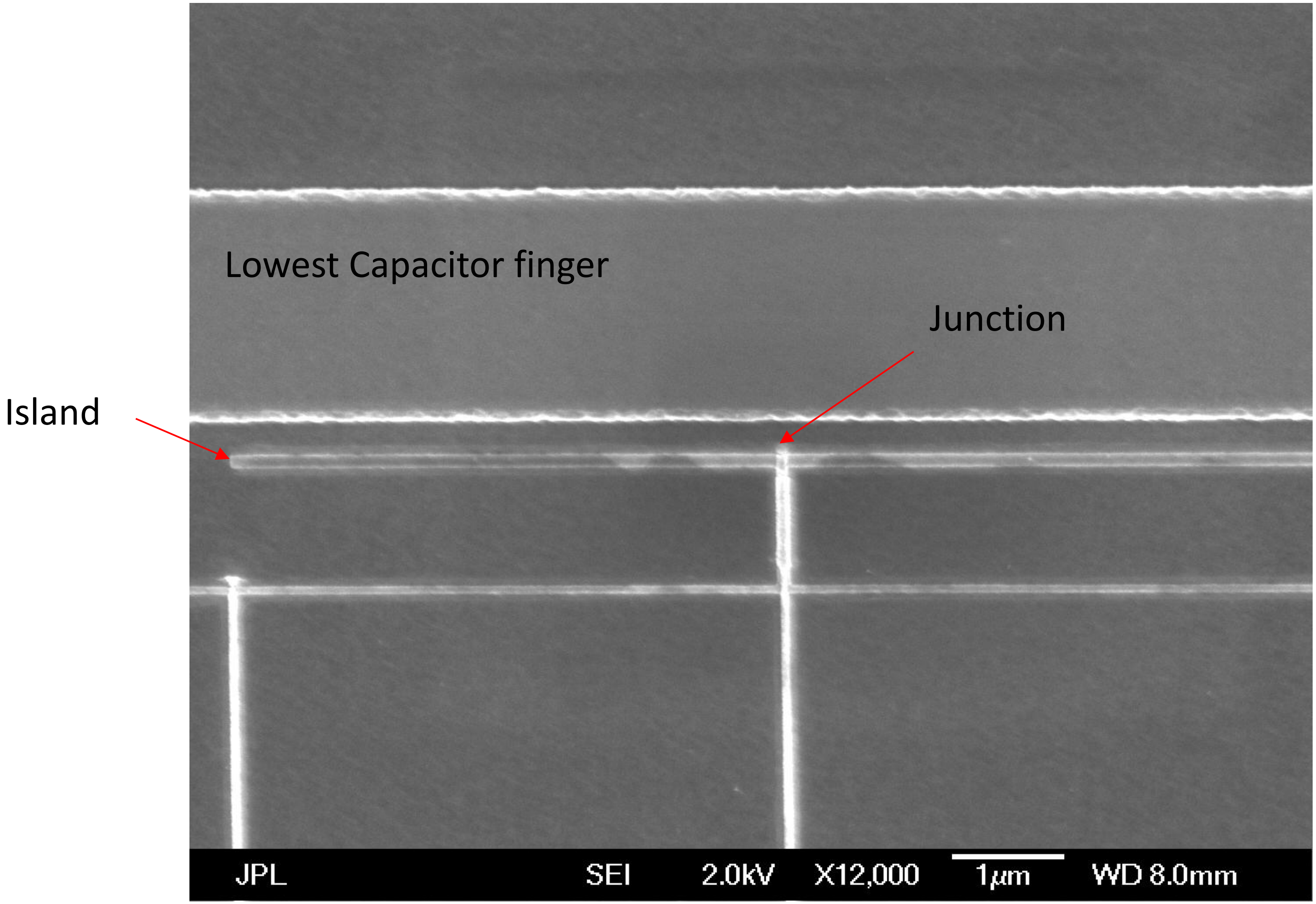


Lens coupled mesh absorber LEQCD

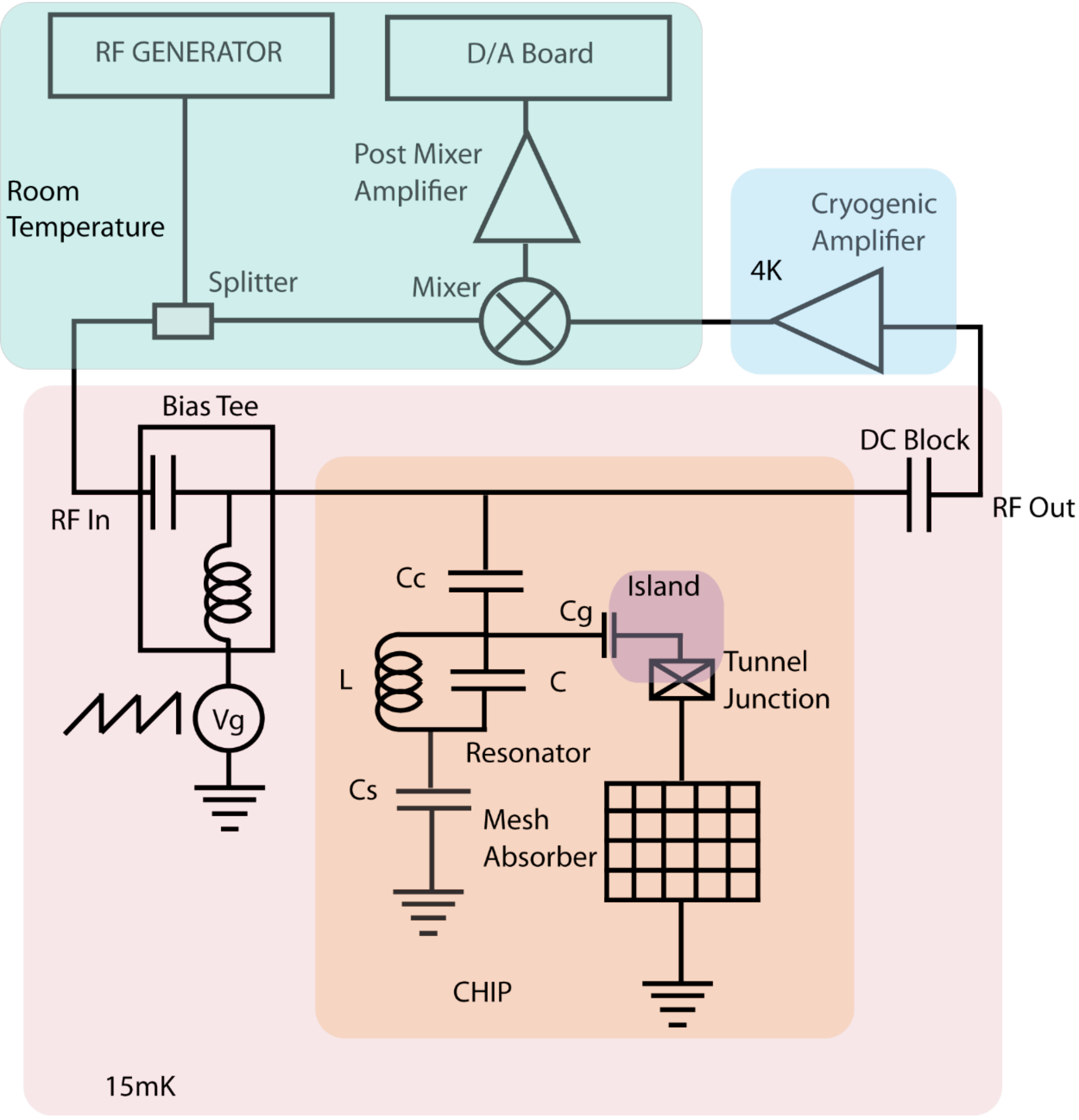
Mesh absorber



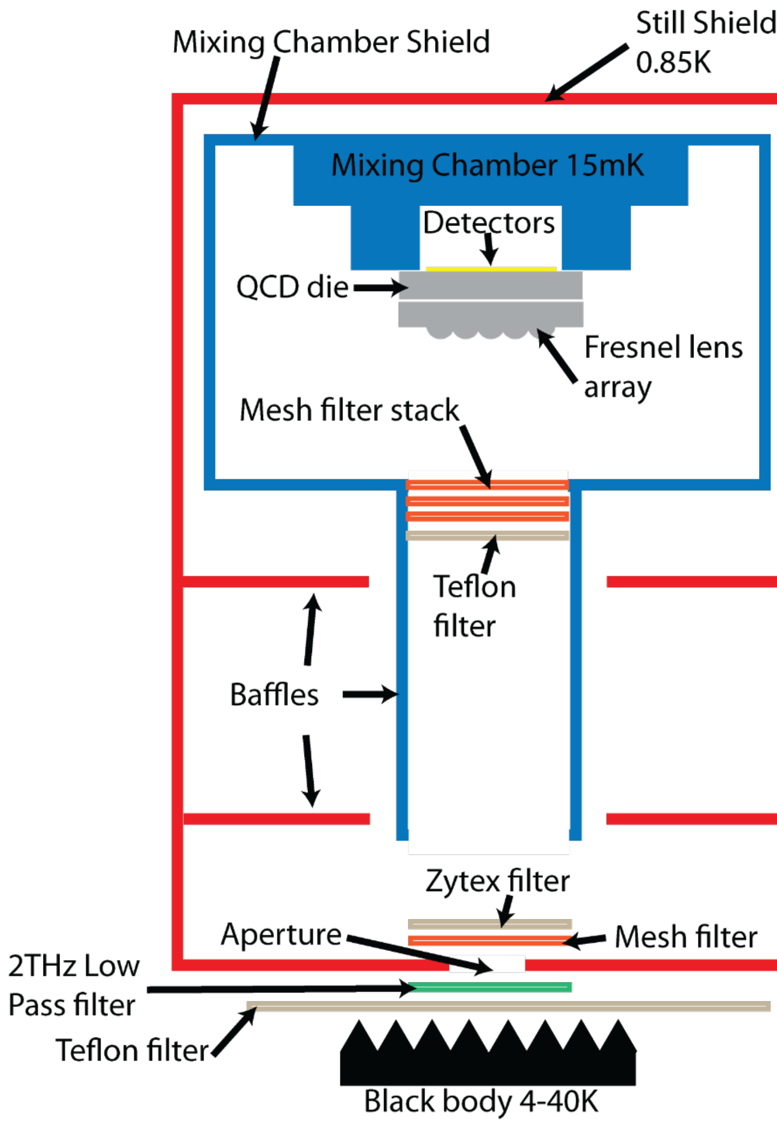
Lens coupled mesh absorber LEQCD



Measurement setup



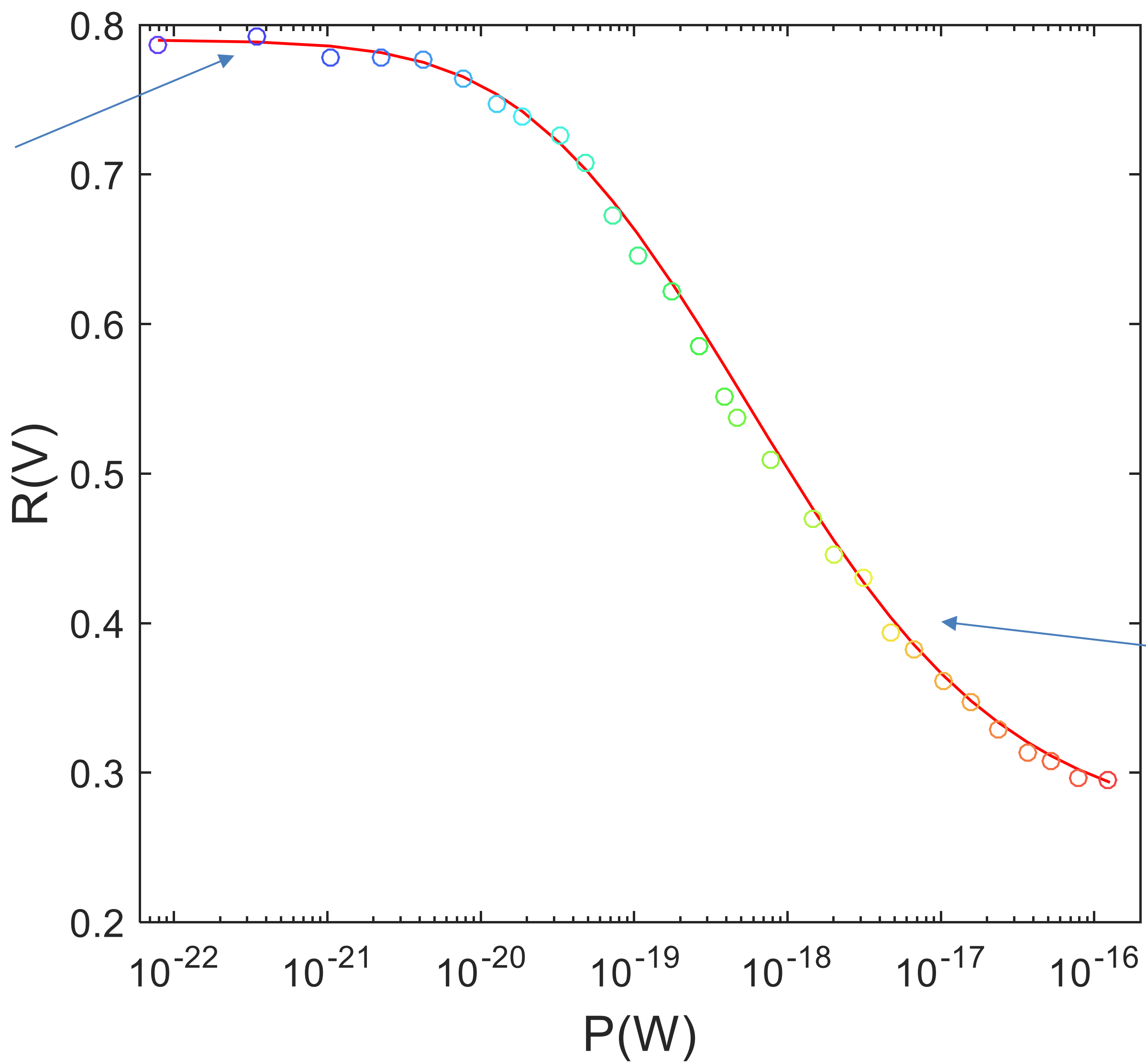
Measurement setup



Lens coupled mesh absorber LEQCD

- QCD response as a function of optical power

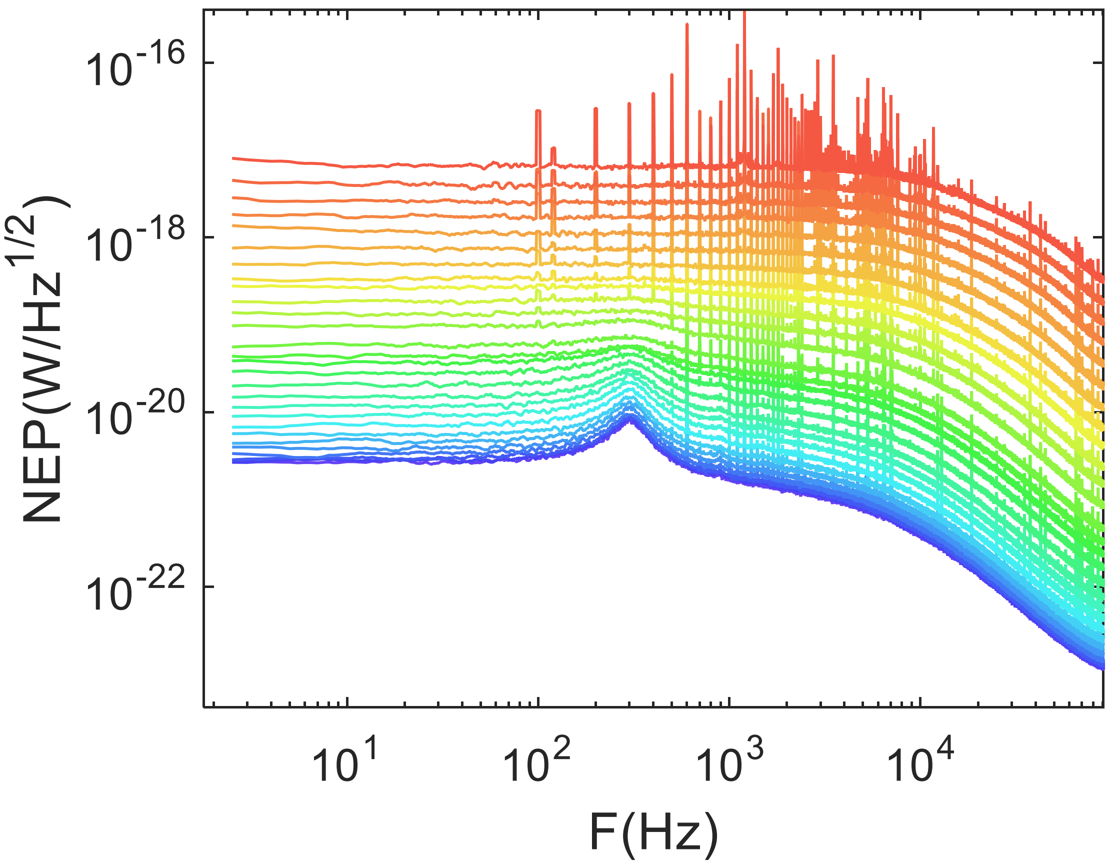
Tunneling in < base tunneling rate



Tunneling In >> Tunneling out -> Reaching saturation

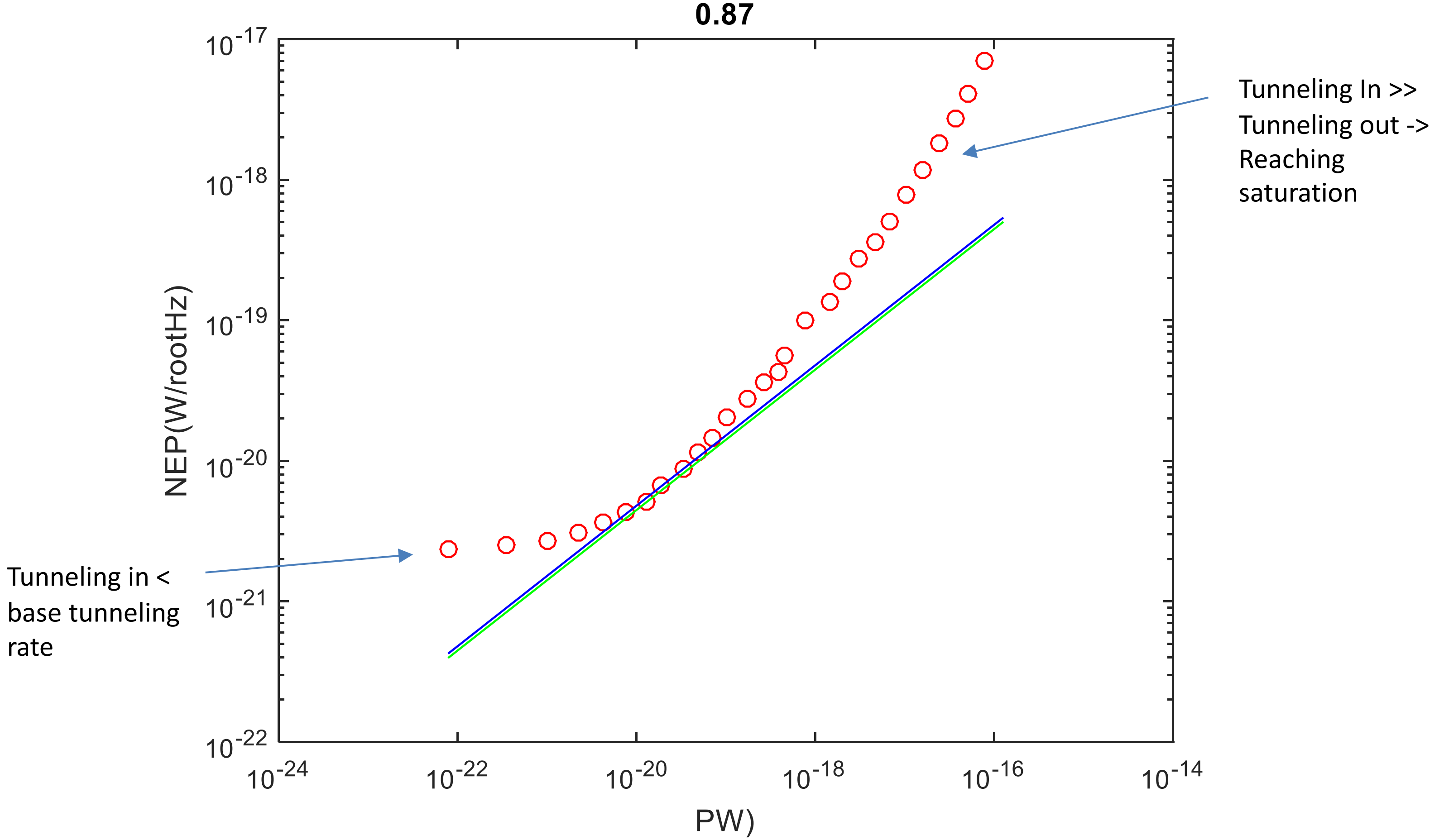
Lens coupled mesh absorber LEQCD

- NEP for various levels of optical illumination



- PSD time span 2s
- Gate sweep frequency 100Hz
- One sweep = 6 peaks
- QC peaks = 600Hz

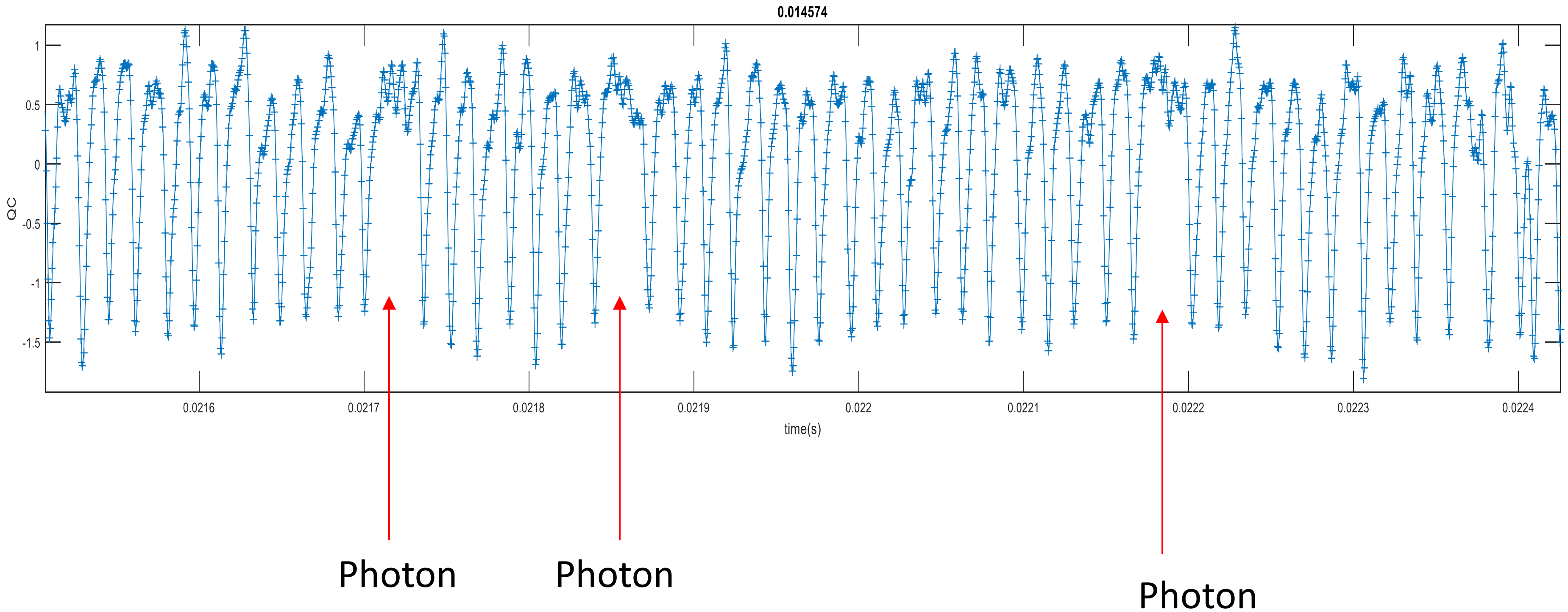
Lens coupled mesh absorber LEQCD



- $P^{1/2}$ dependence implies photon noise limited performance
- Efficiency extracted form ratio of measured NEP and photon shot noise NEP
- Should be able to detect single photons

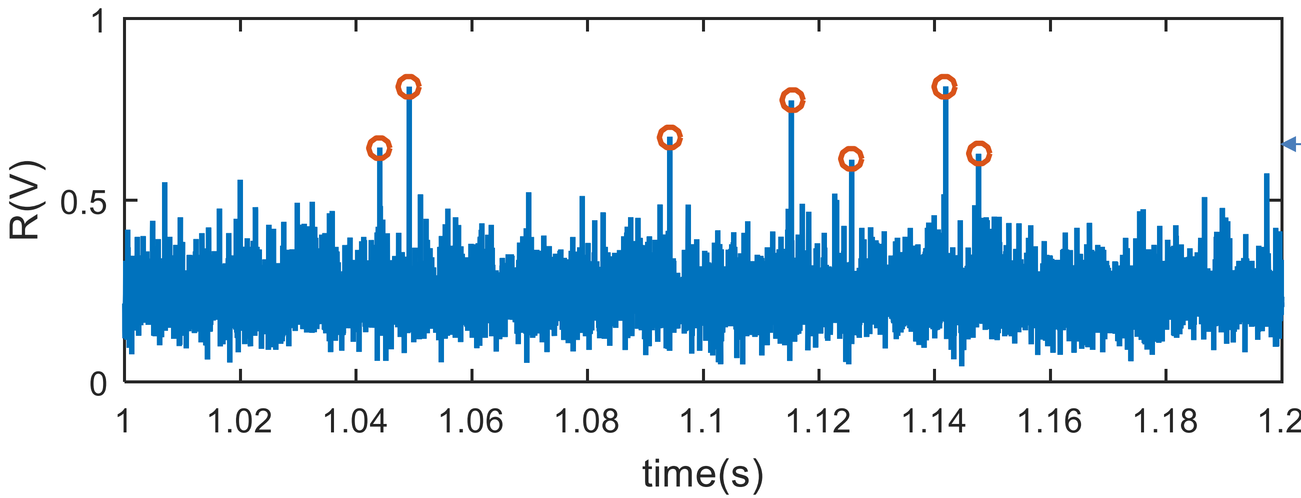
“ Fast sweep reveals single photon events spoiling QC signal

- Sweep rate ~ 22kHz spanning 3 Quantum Capacitance Peaks => effective sweep rate ~ 66kHz
- Should block background tunneling while still allowing tunneling due to single photon absorption
- Raw QC time trace should be absolutely periodic
- Gaps are due to high tunneling suppressing the Quantum Capacitance signal
- Therefore Gaps should be due to single photon absorption

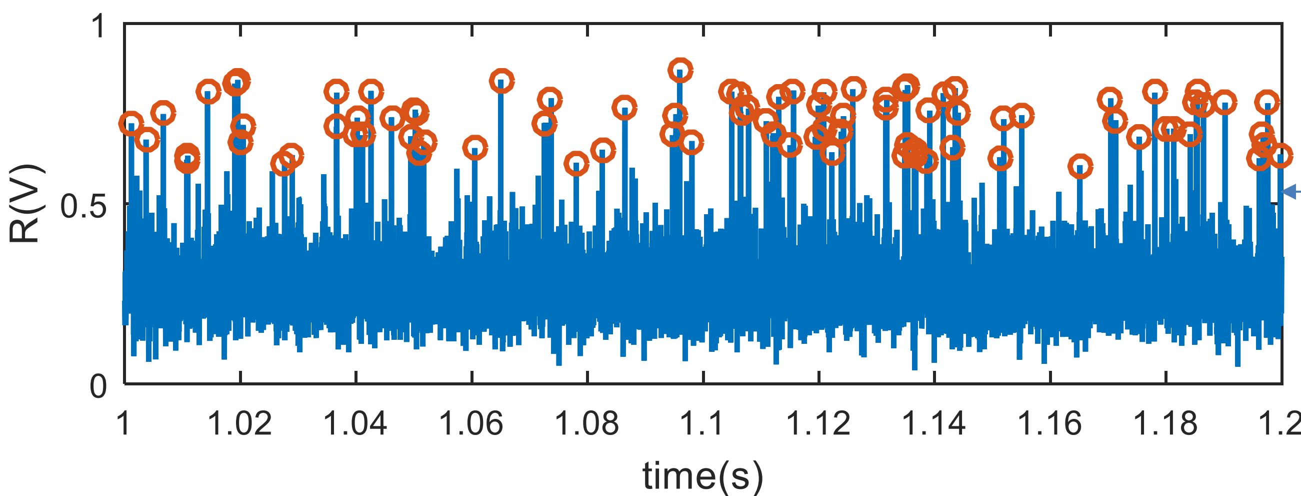


Variance evaluated in 30 us bins shows photon events

- From time traces calculated variance of slices corresponding to 2 QC peaks (to avoid problems at the edge of sweep with e-shifts) – slices are 30μs long
- Subtracted this trace from the maximum of the traces
- Gaps in the Quantum Capacitance trace will show up as peaks
- Repeat for different black body source temperatures



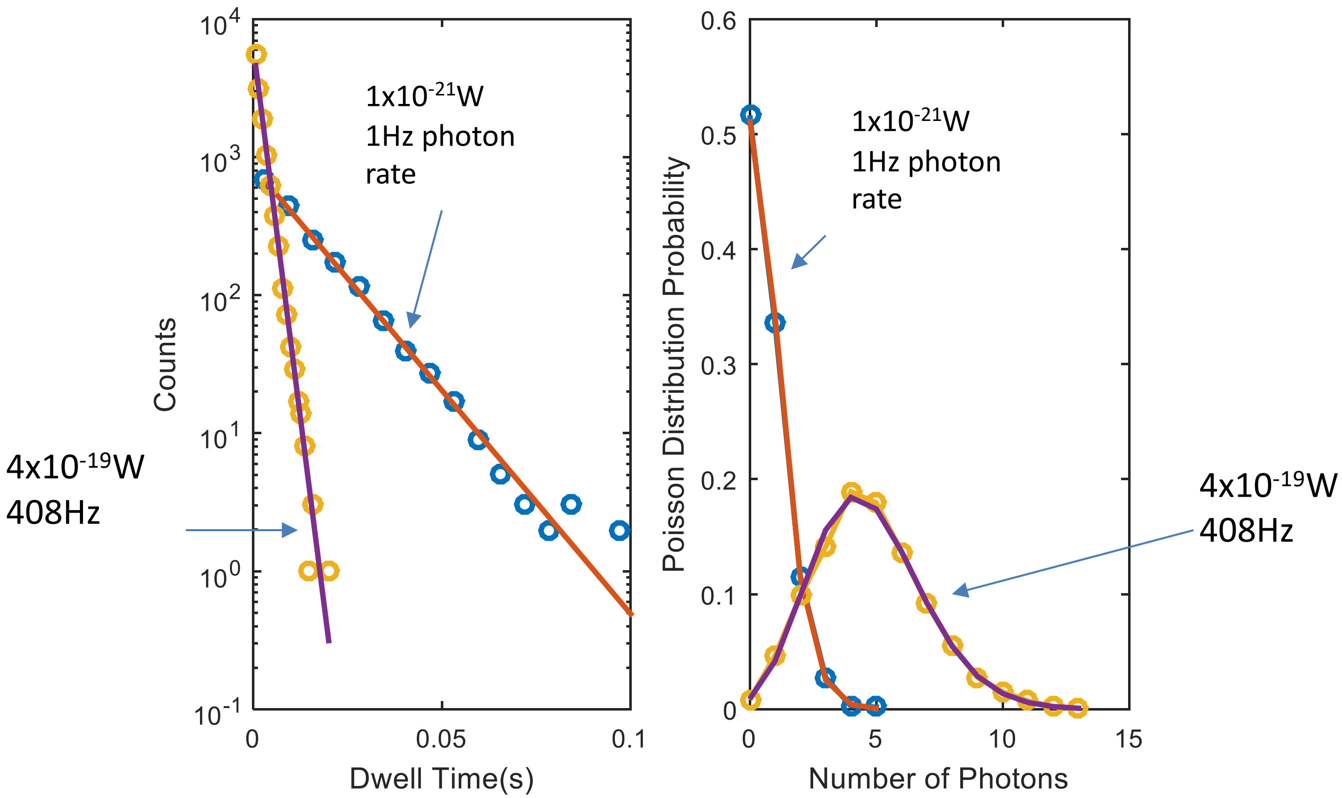
$1x10^{-21}$W
1Hz photon
rate



$4x10^{-19}$W
408Hz

Photon arrival intervals follow Poisson statistics

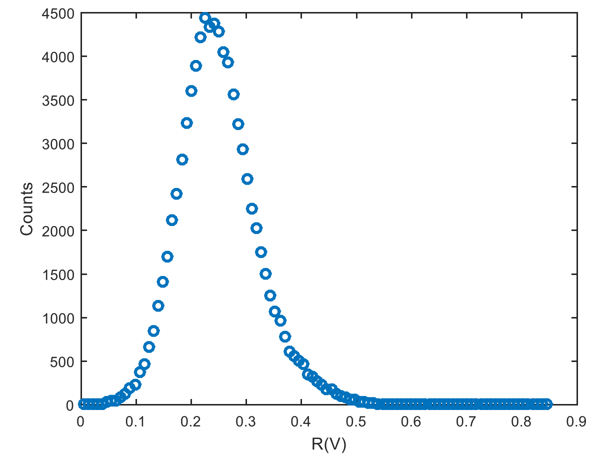
- From the photon time traces, extract dwell time histograms – exponential decay corresponds to Poisson statistics
- Calculate probability of having N photons within a time interval 36ms (Arbitrarily picked)
- Plot probability x number of photons; blue circles is measured, lines are calculated Poisson distribution probability (no fit, just using measured average number of photons)



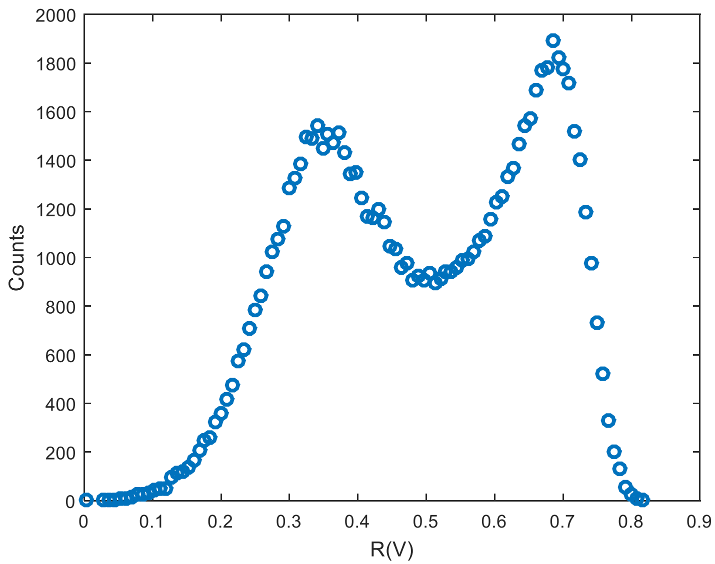
Photon arrival statistics

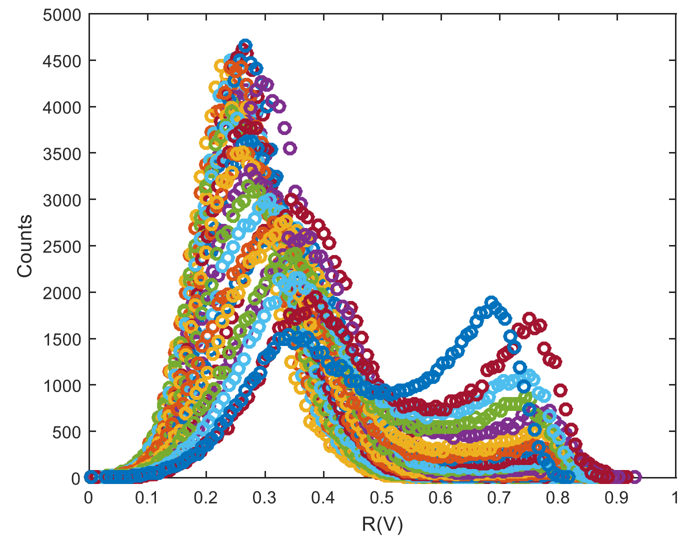
Histogram of response for various black body temperatures
For cold black body only peak around 0.25 exists
For hot black body peak around 0.6-0.7 is larger than peak at 0.25

Cold black body



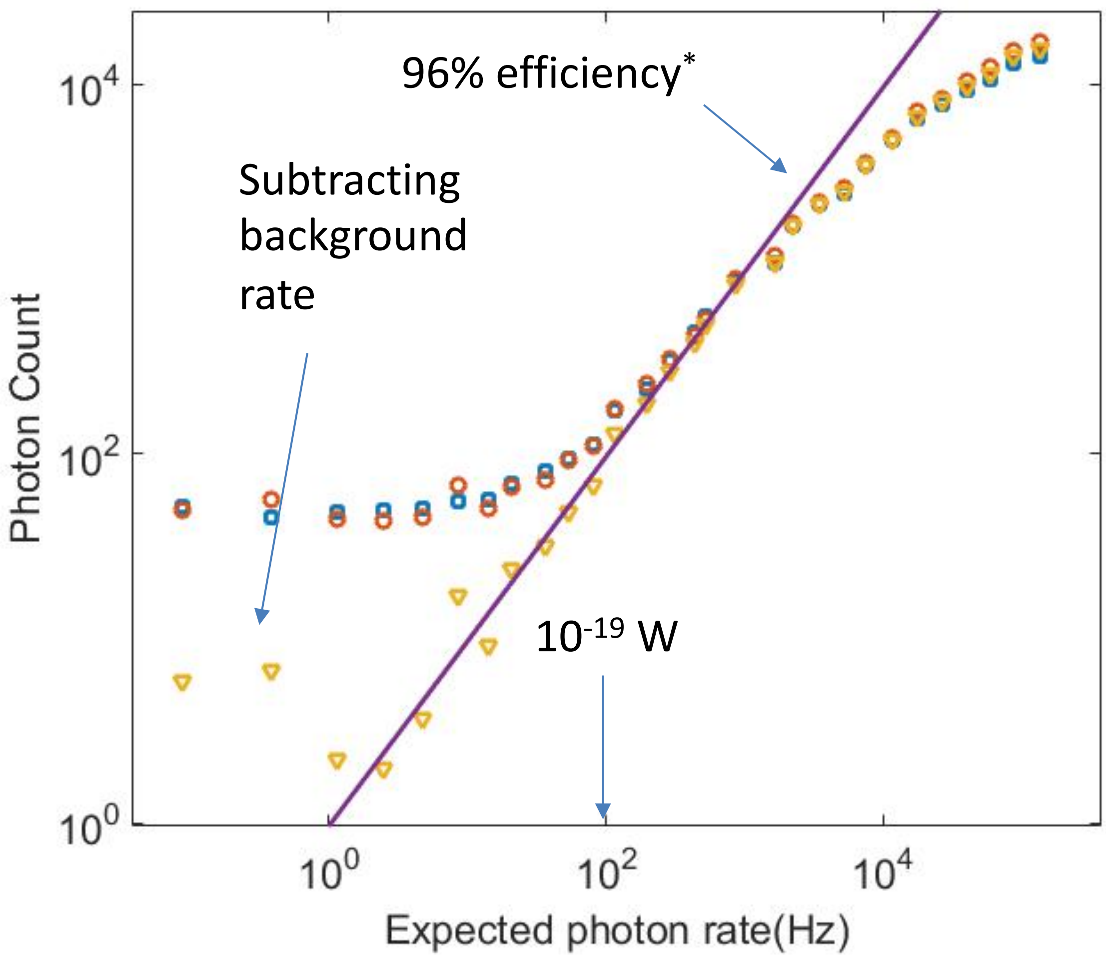
Hot black body





- Peaks get closer together at high black body temperatures due to filtering by the resonator of the high frequency stream
- Could lower resonator Q by stronger coupling at the expense of fewer channels

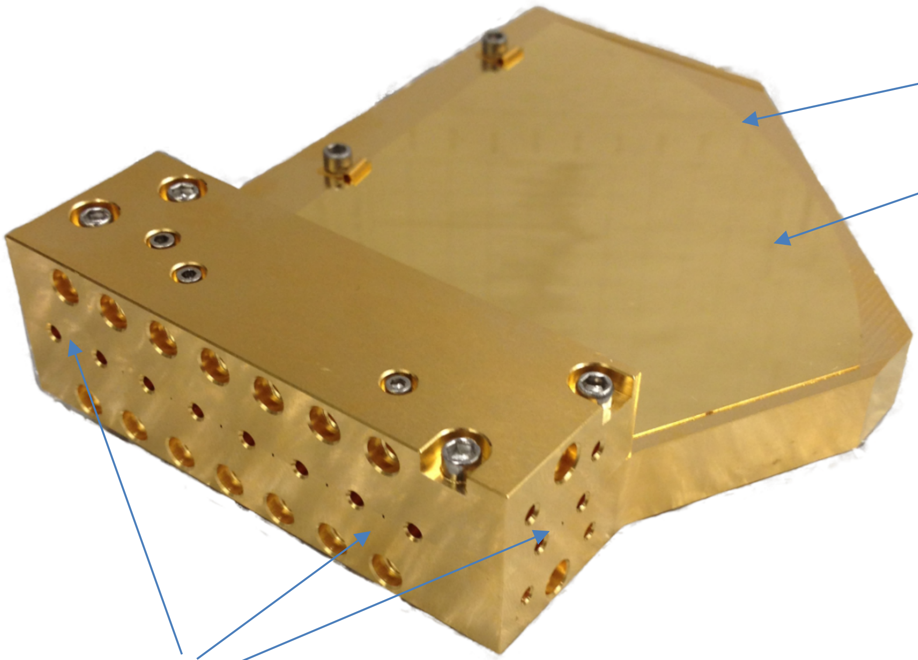
Counts of response between 0.6 and 0.9 versus number of expected photons



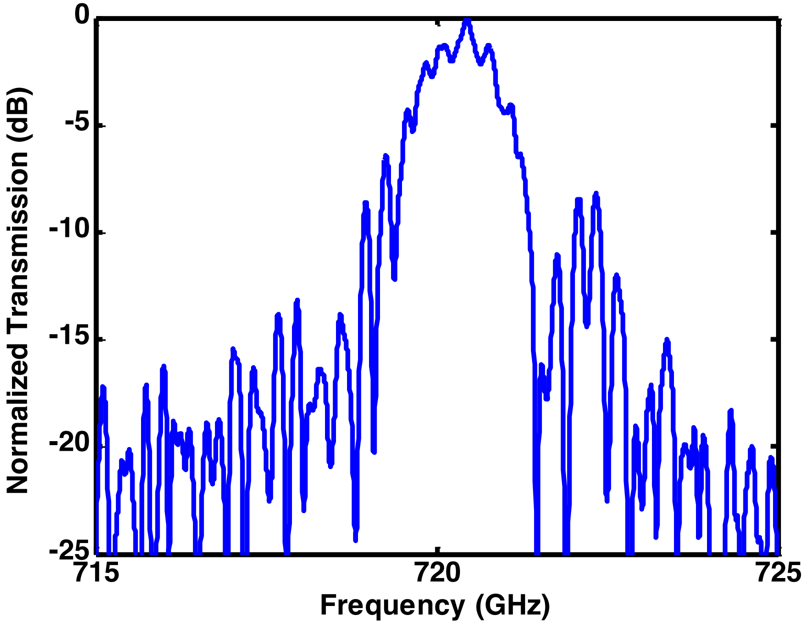
- Efficiency will decrease with when time intervals between photons become comparable to the time separation of two Quantum Capacitance Peaks

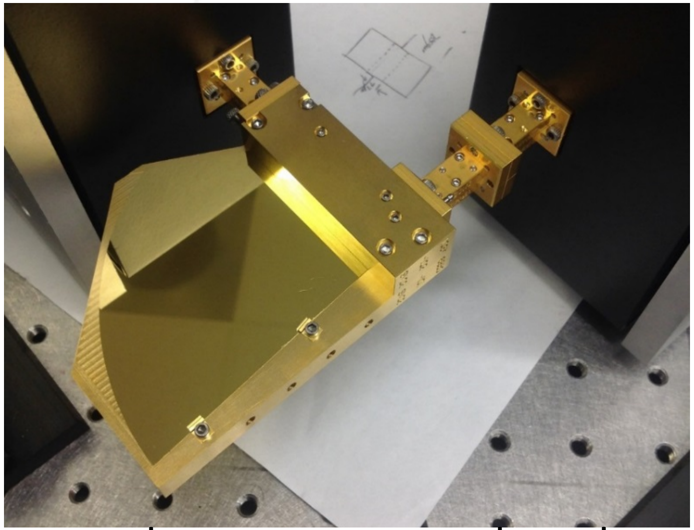
* With respect to absorbed power

Grating spectrometer on a wafer



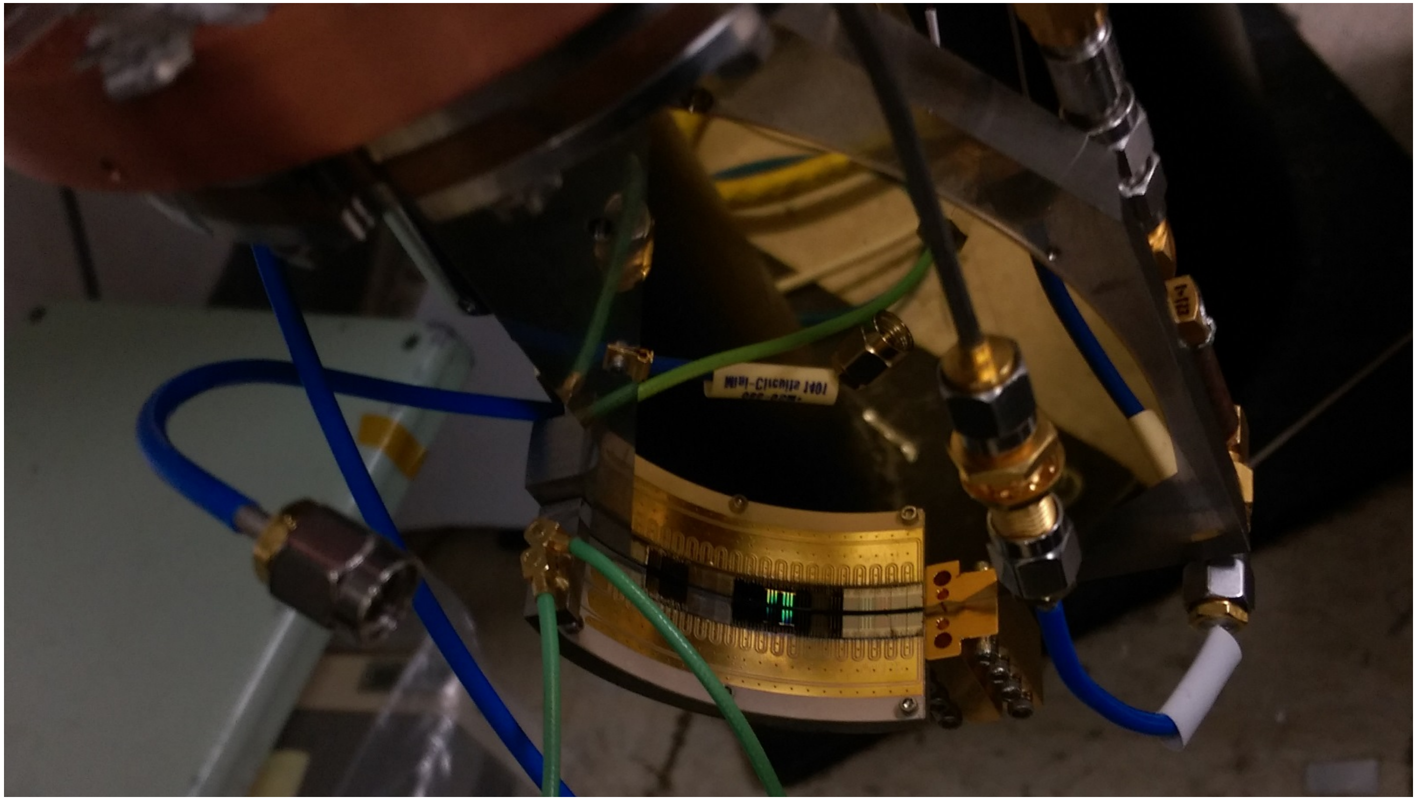
- VNA measurement of transmission between input feed and 720GHz output feed
- R ~ 600





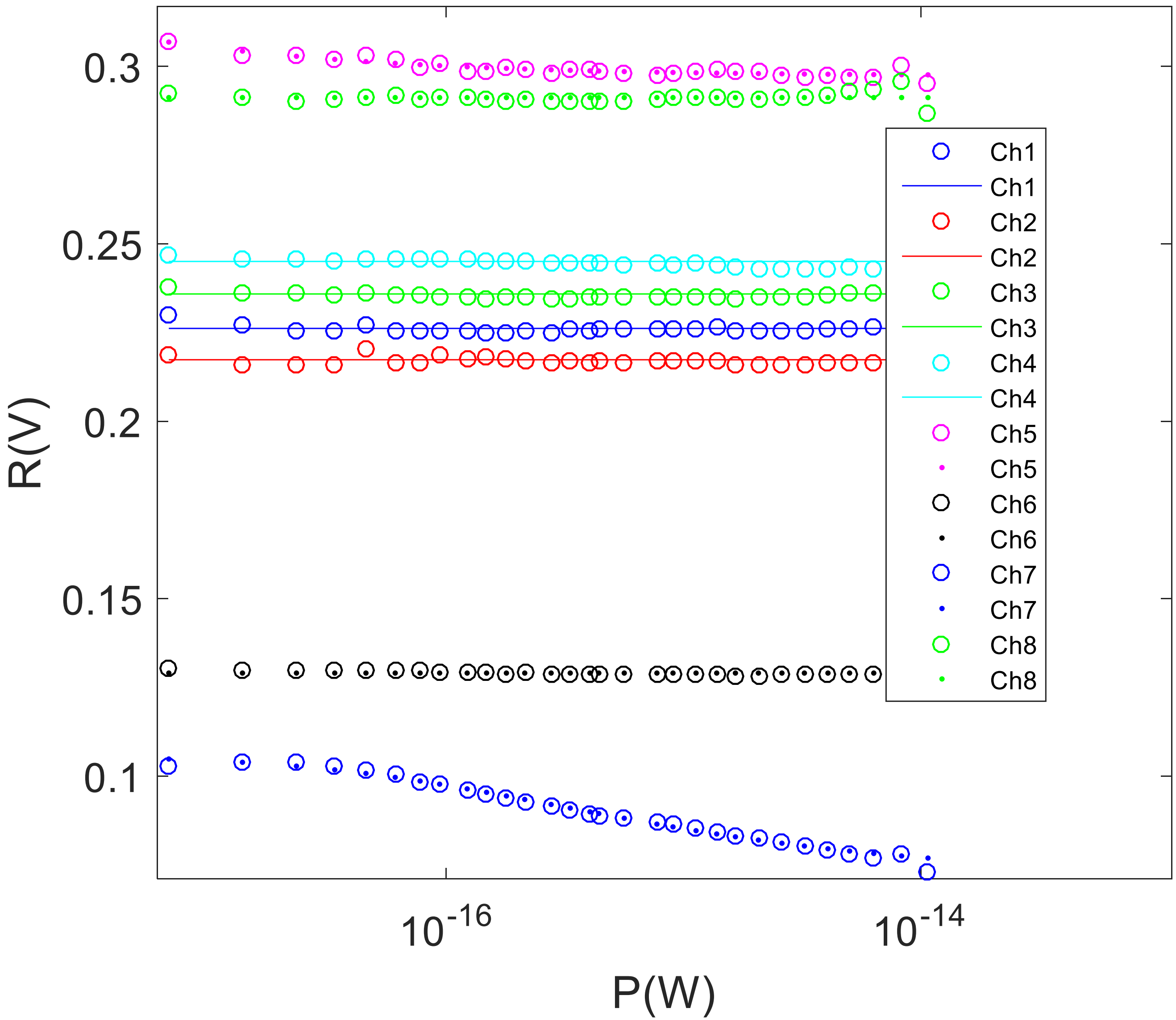
Connected to vector network analyzer

Integrating Spectrometer and QCDs



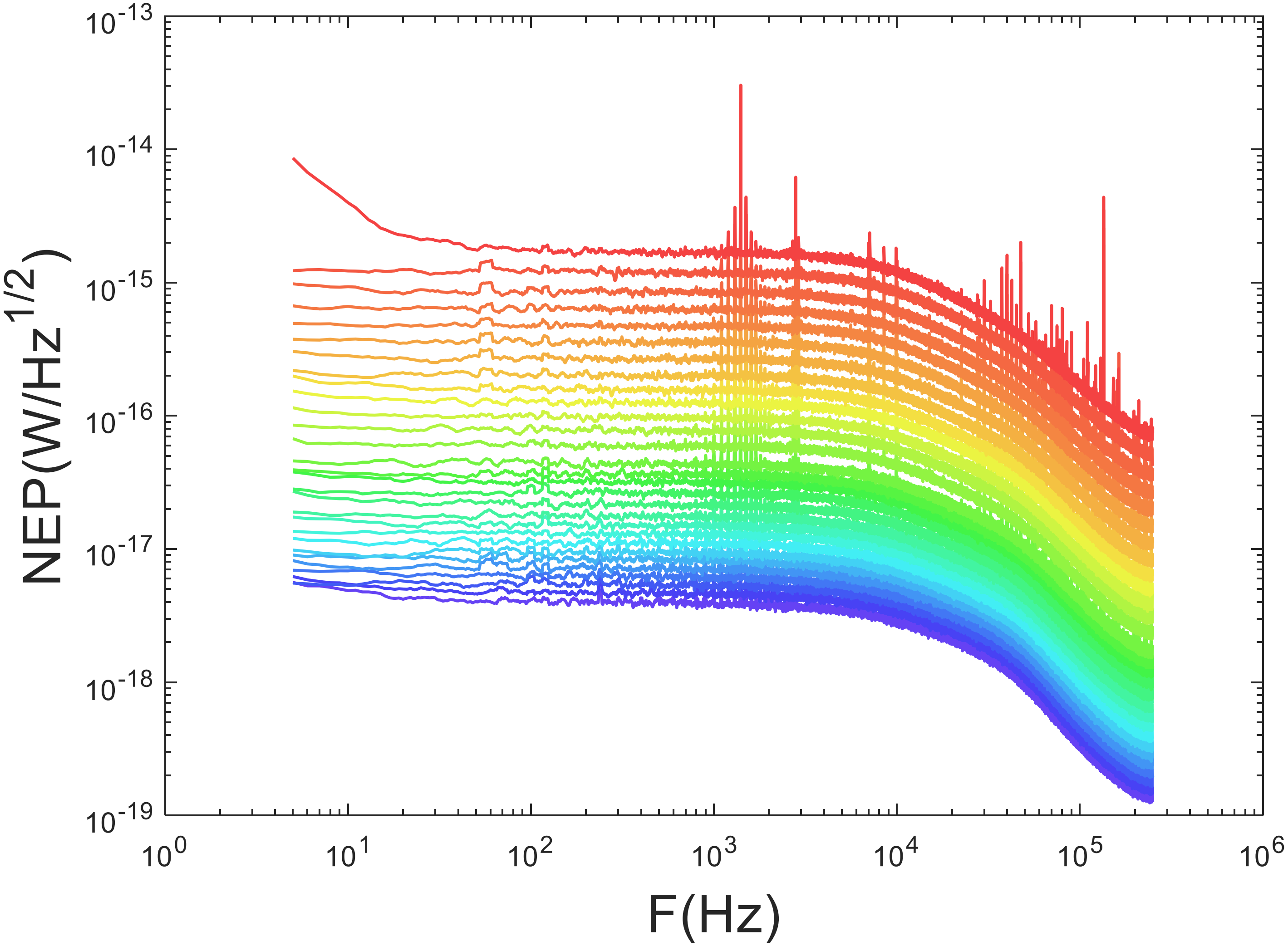
- Spectrometer wafer input feed is very fragile – broke multiple feeds (have to replace spectrometer wafer each time
- Readout array requires lots of wire bonds - challenging to cool down without breaks

Testing integrated Spectrometer and QCDs

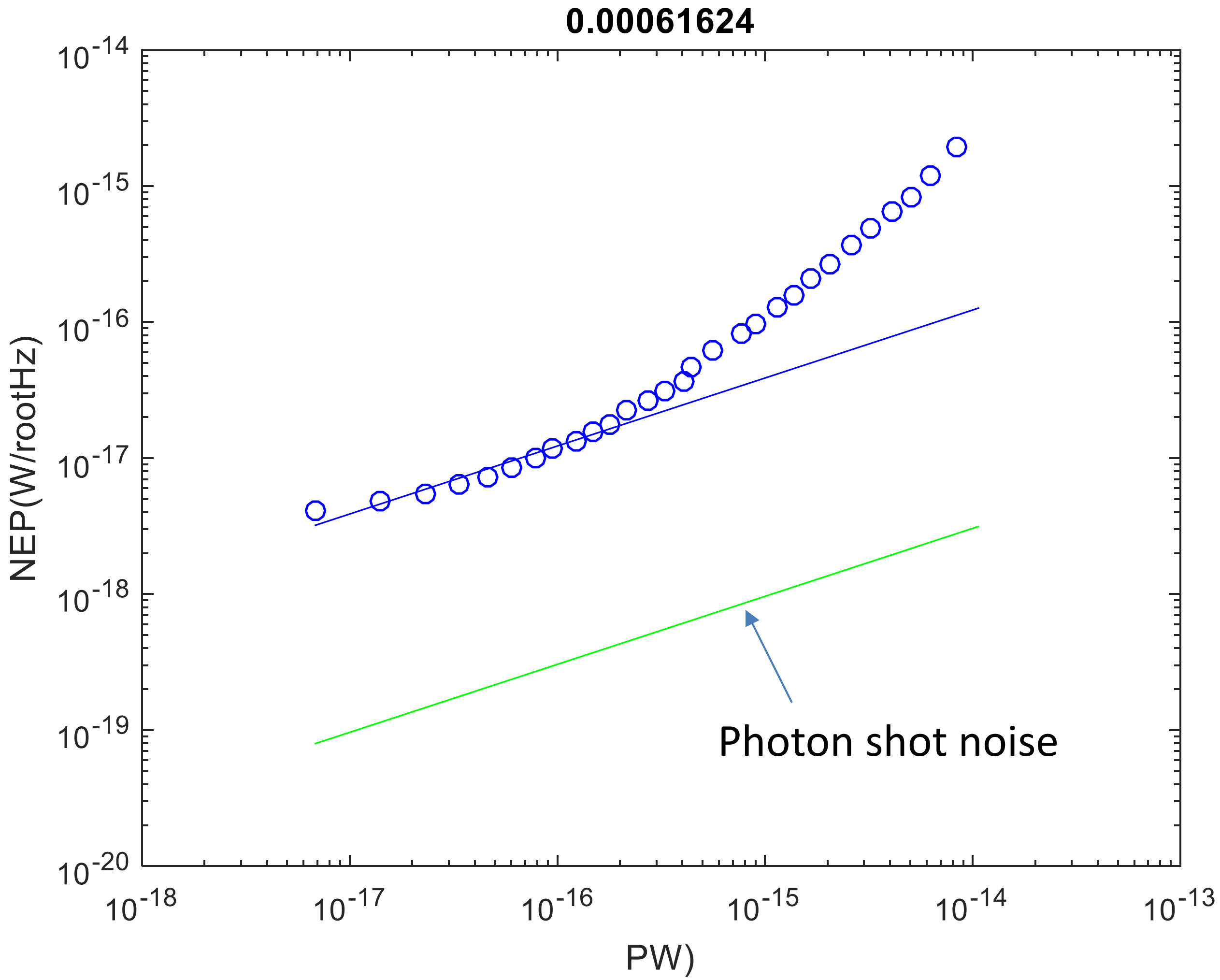


- Small quantum capacitance signal
- Only one channel responding to illumination
- Large aperture (5.5 mm) -> larger powers than usual ->
- Low efficiency

Testing integrated Spectrometer and QCDs

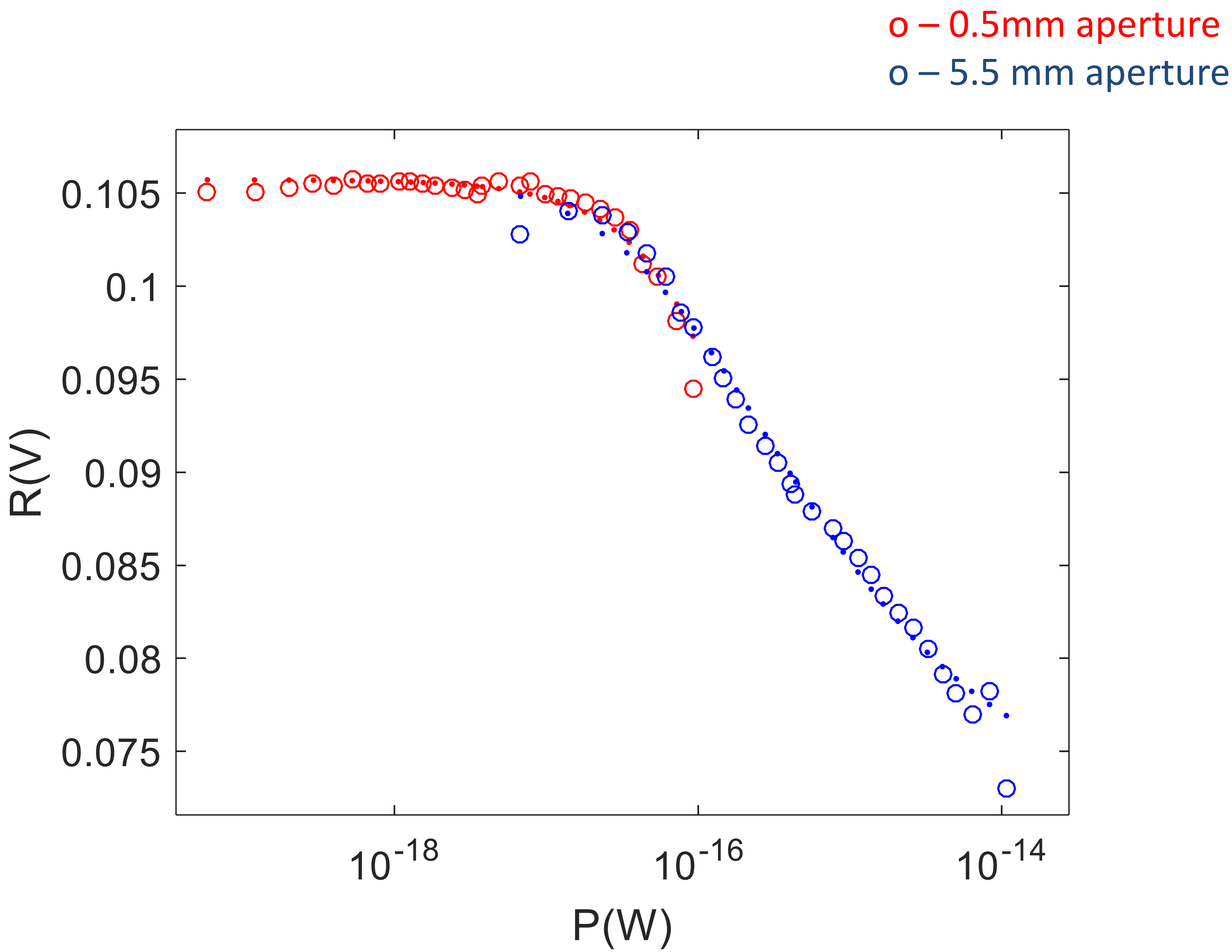


Testing integrated Spectrometer and QCDs

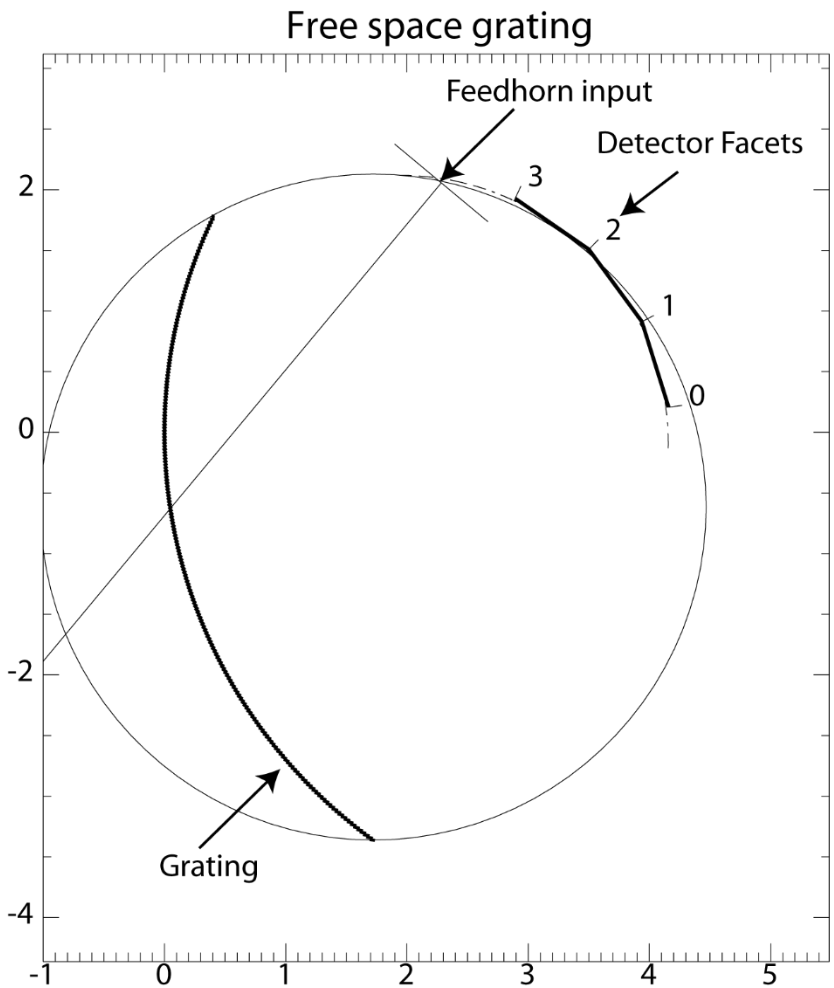


Very low efficiency – 0.06%

Testing integrated Spectrometer and QCDs

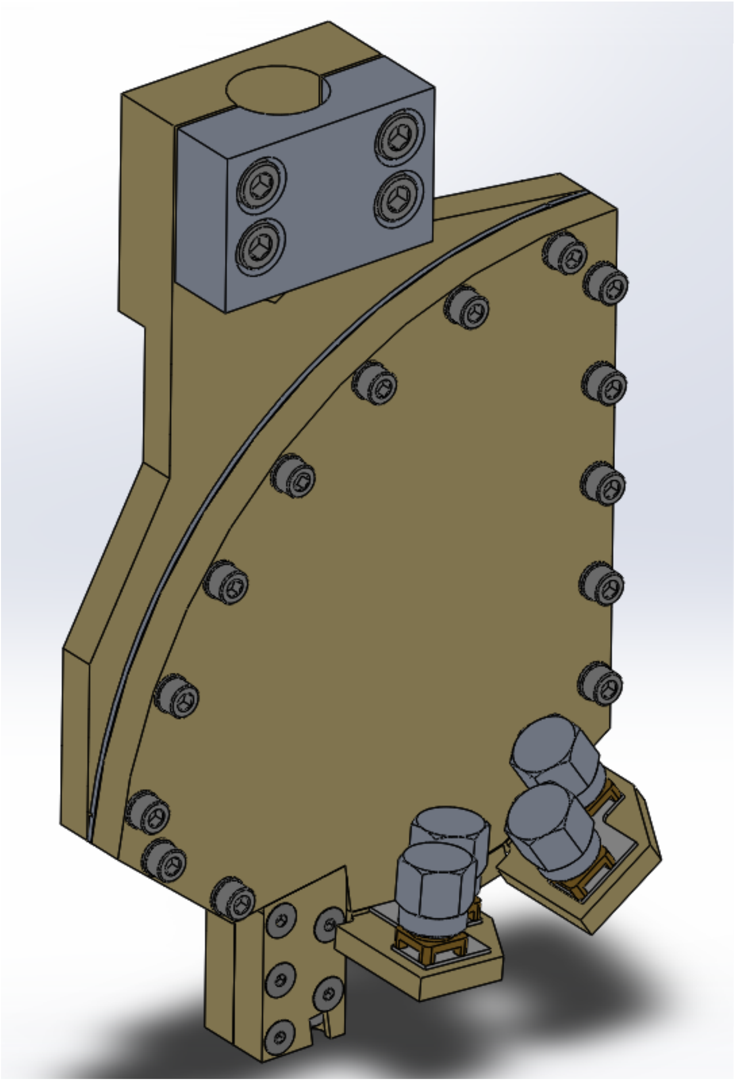


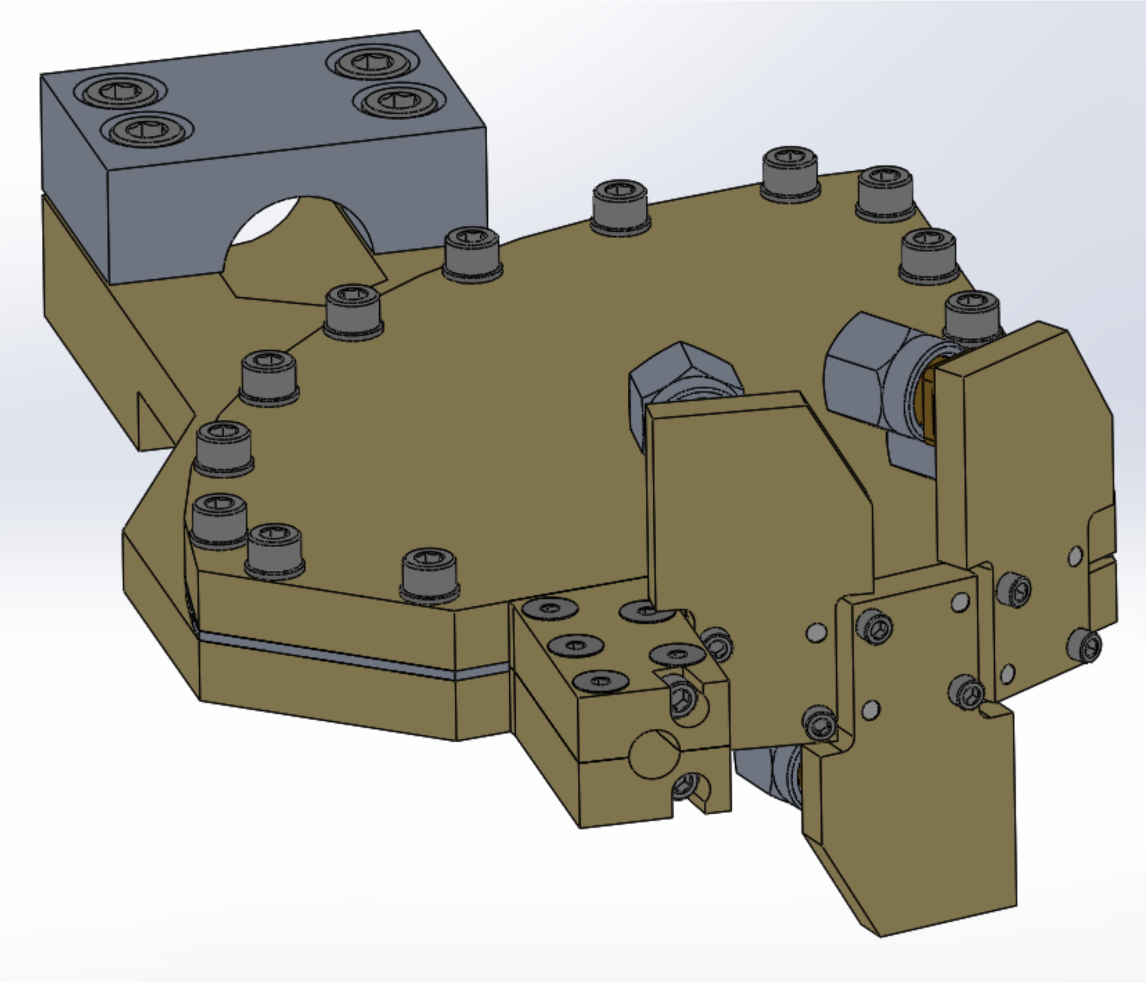
Free space spectrometer



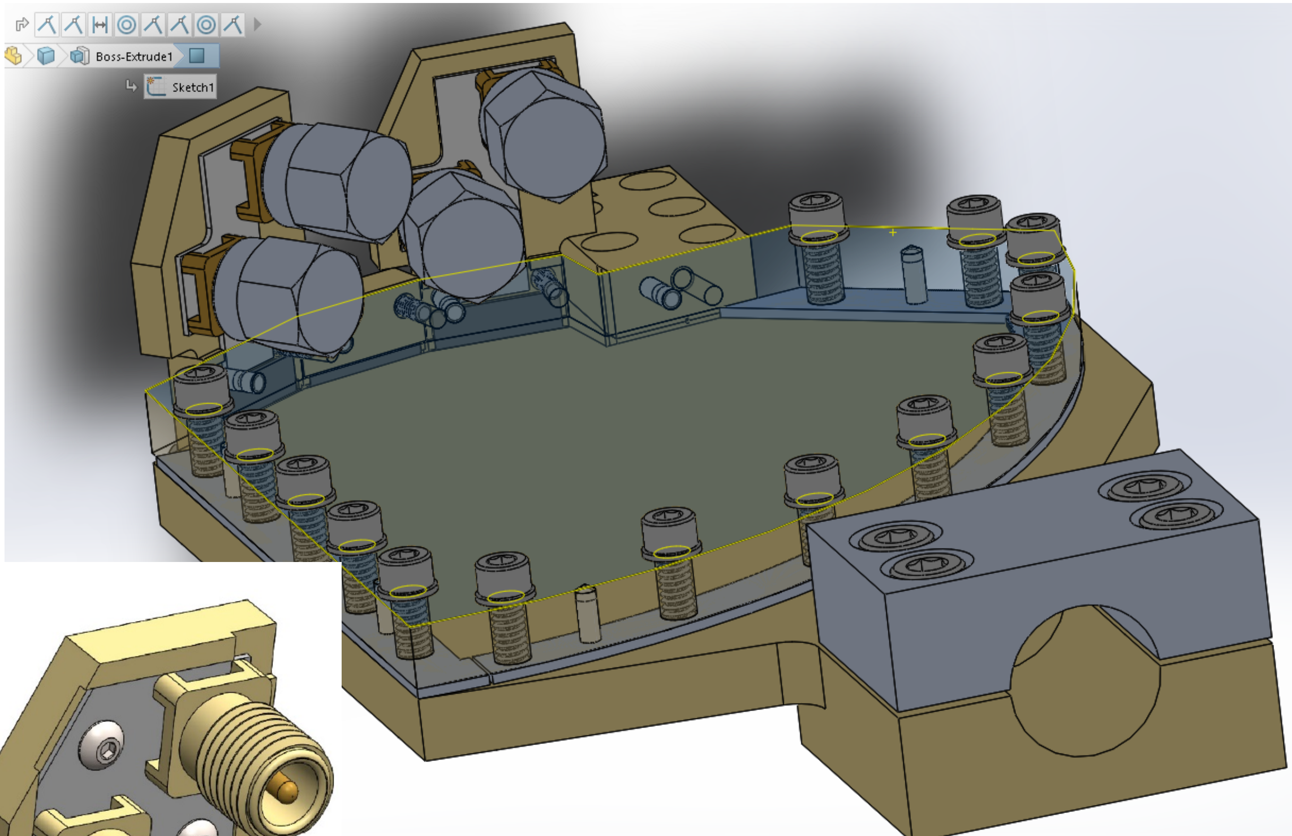
- Free space grating to avoid fragility of silicon input feed
- 860GHz to 1.8THz, 550-950GHz for silicon spectrometer
- R ~ 140 (600 measured on silicon spectrometer)
- 3 detector chips as opposed to 19. Easier assembly and better RF performance

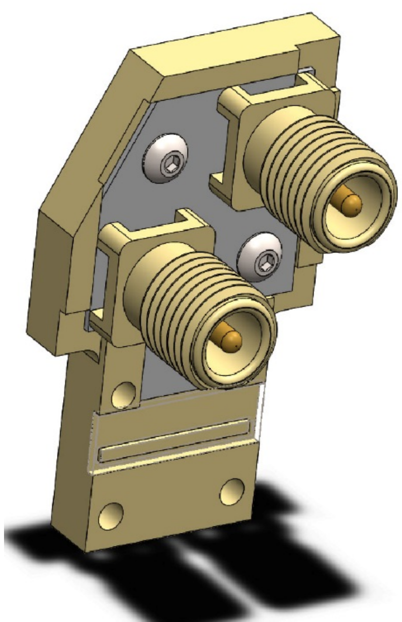
Grating spectrometer design

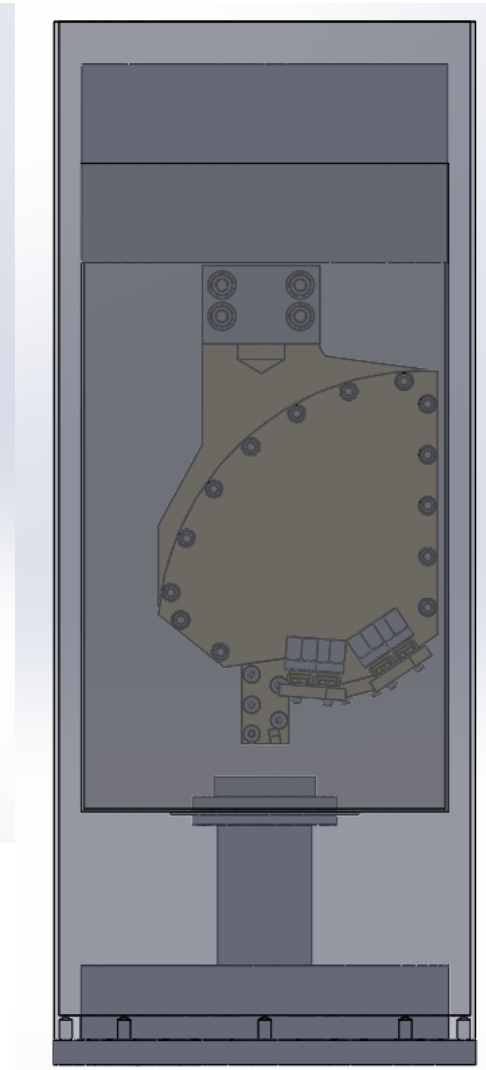




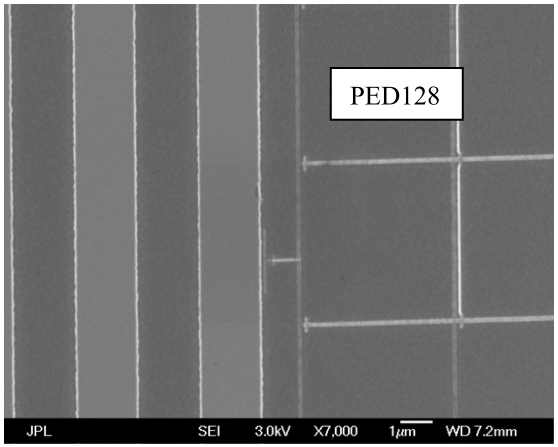
Grating spectrometer design

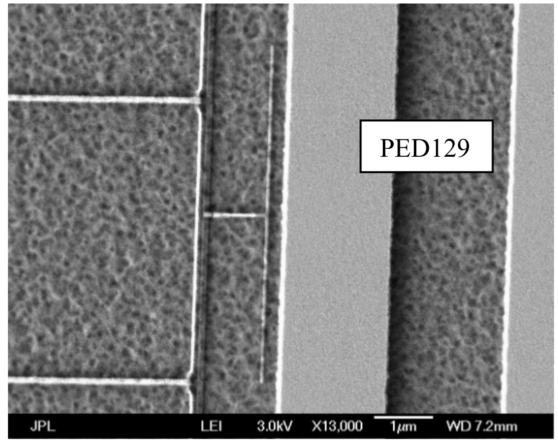


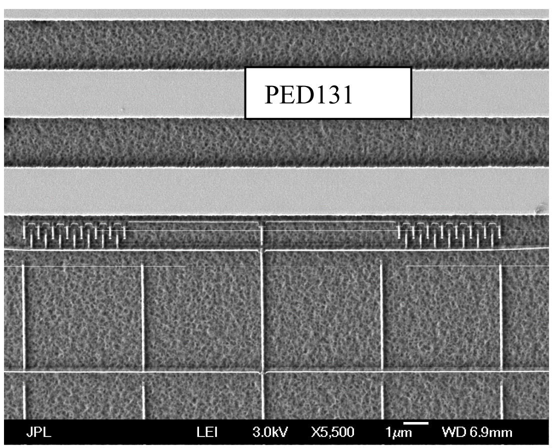


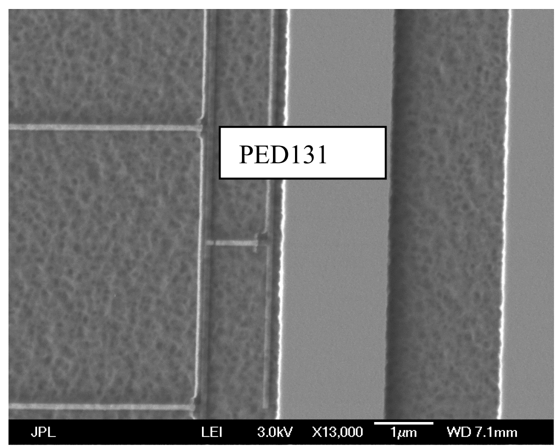


QCD arrays - yield



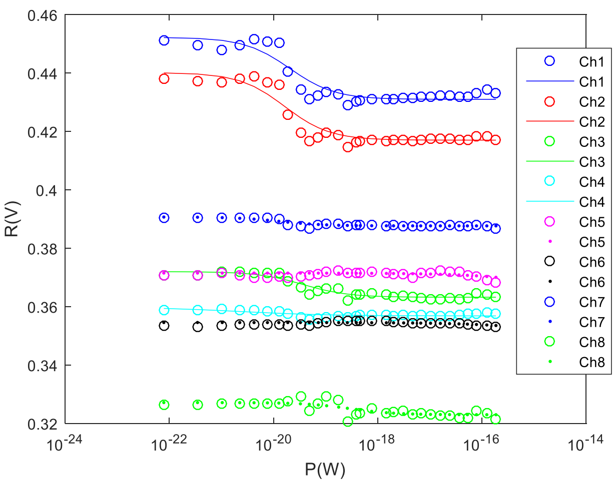


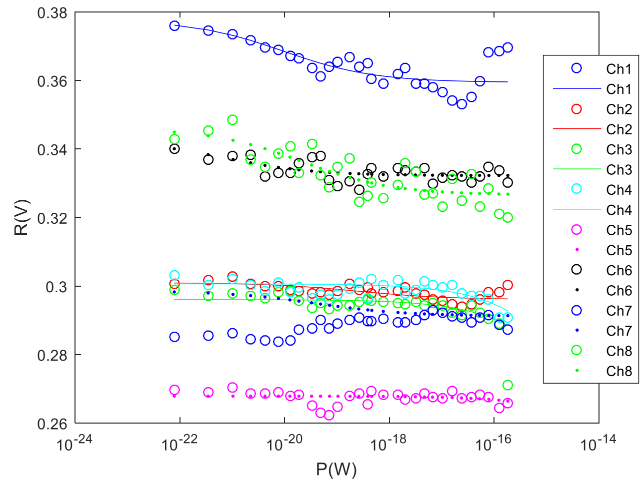




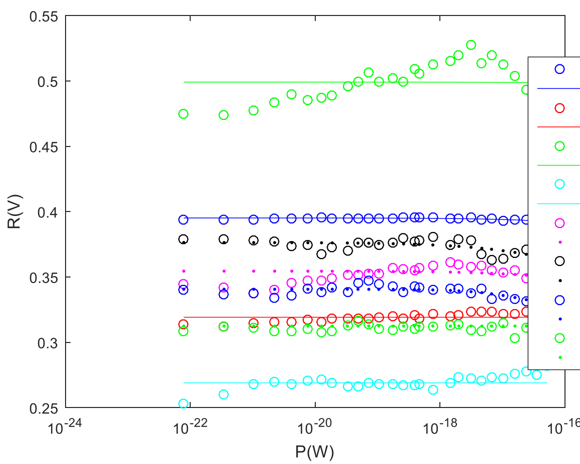
- Move critical tunnel junction away from large structures
- Study rate of tunneling out as a function of island volume
- Decrease charging energy to increase tunneling out rate
- All written at 48kV
- All had “flags” possibly shorting out mesh absorber

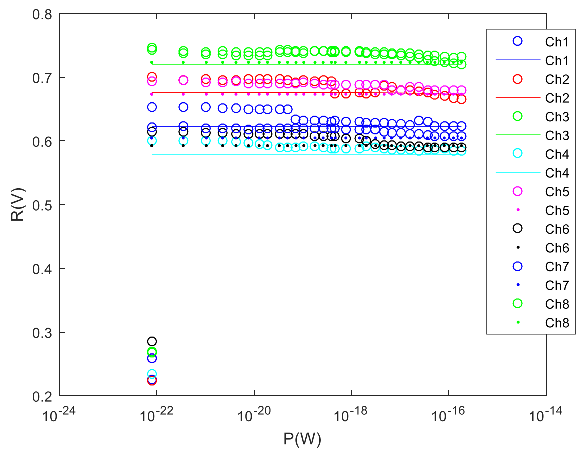
QCD arrays -yield



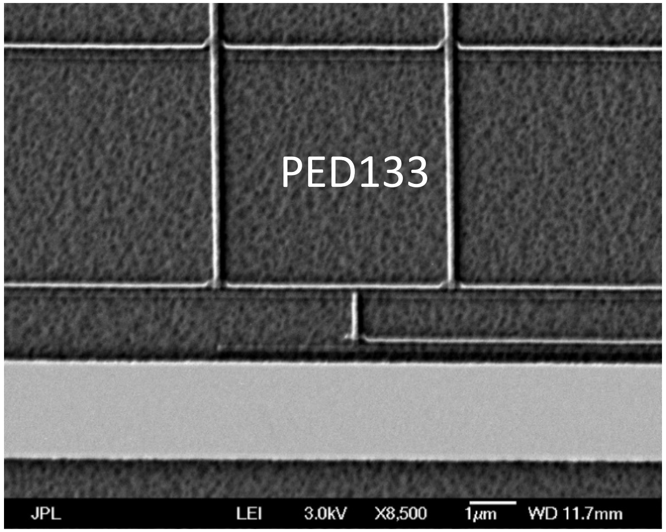


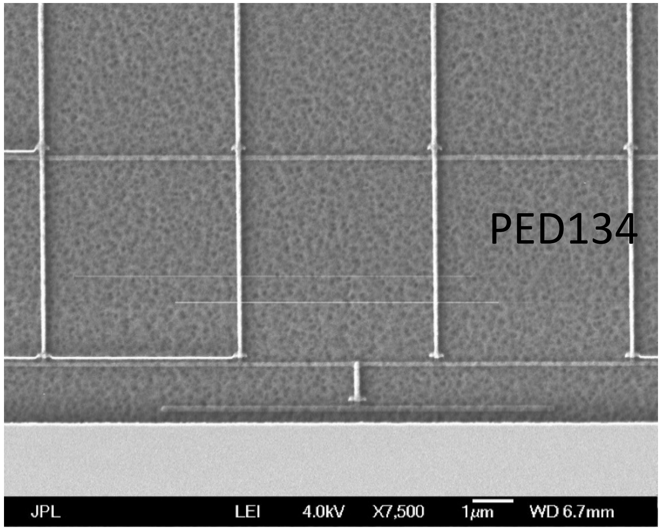
- No dependence of QC on optical illumination level
- Poor yield on quantum capacitance signal
- PED128 -8 out of 25
- PED129 – 15 out of 25
- PED131 - 10 out of 25 (5 with good signal to noise ratio)
- PED132 – 8 out of 25

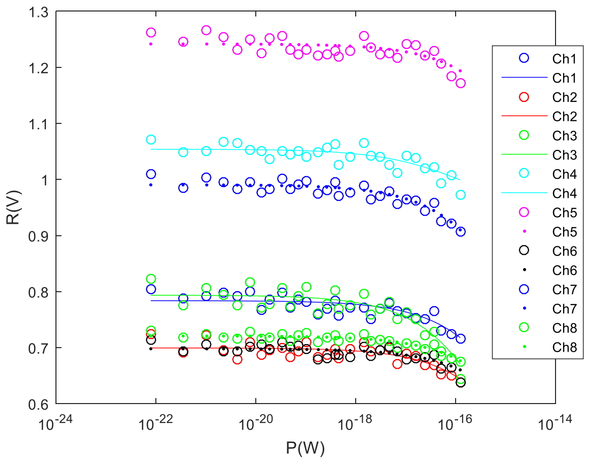


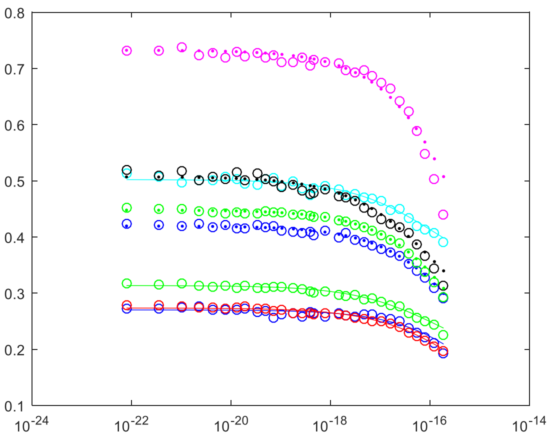


QCD arrays - yield



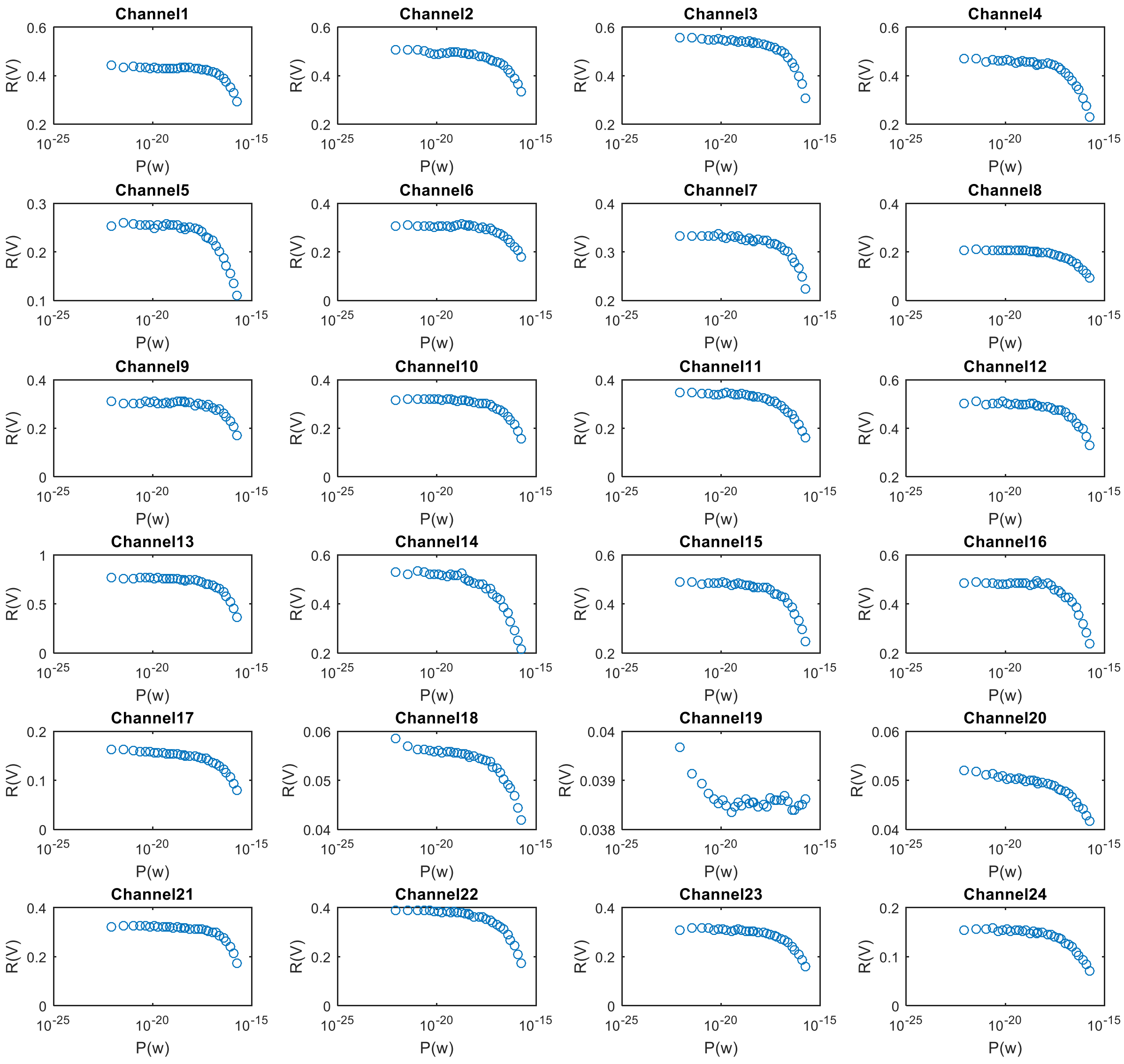




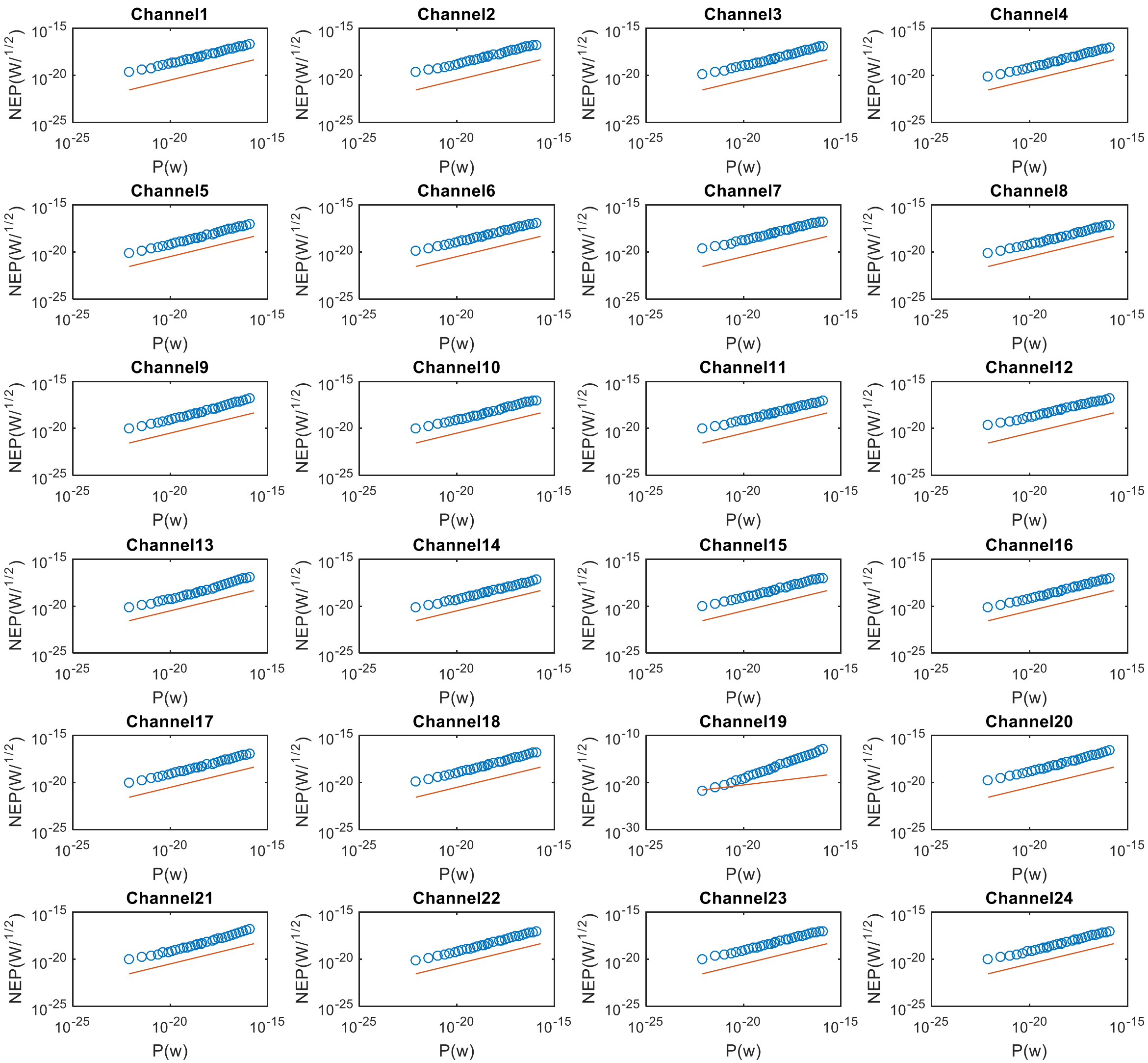


- Switched to 100kV E-beam lithography
- PED133 – 20 out of 25
- Some optical response
- Still flags present
- PED134 – narrower Mesh absorber lines
- Fewer flags (but still present in ~ 50%
- 23 out of 25 large QC signals
- Better optical response
- Efficiency still ~ 1%

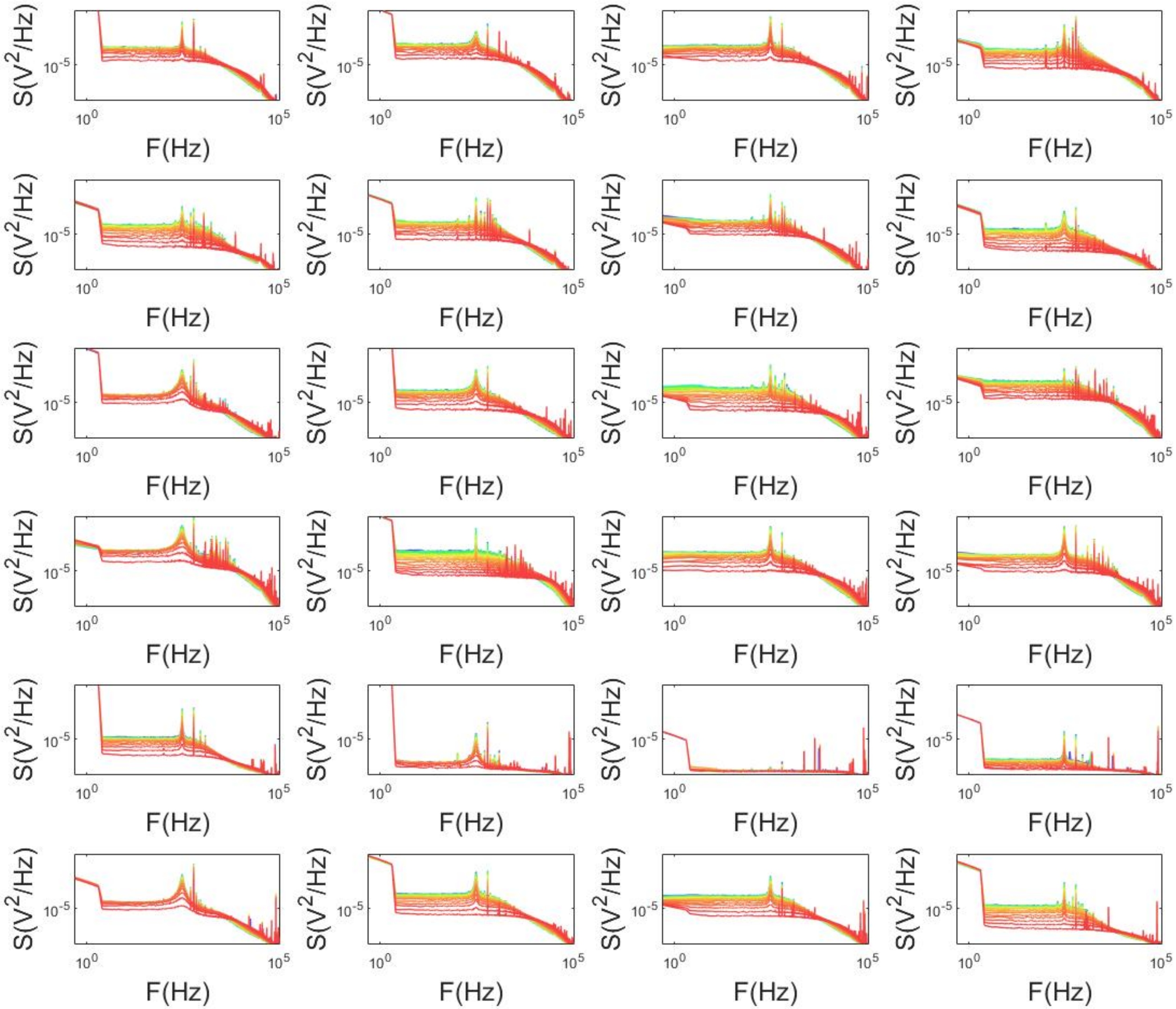
PED134 – all channels response



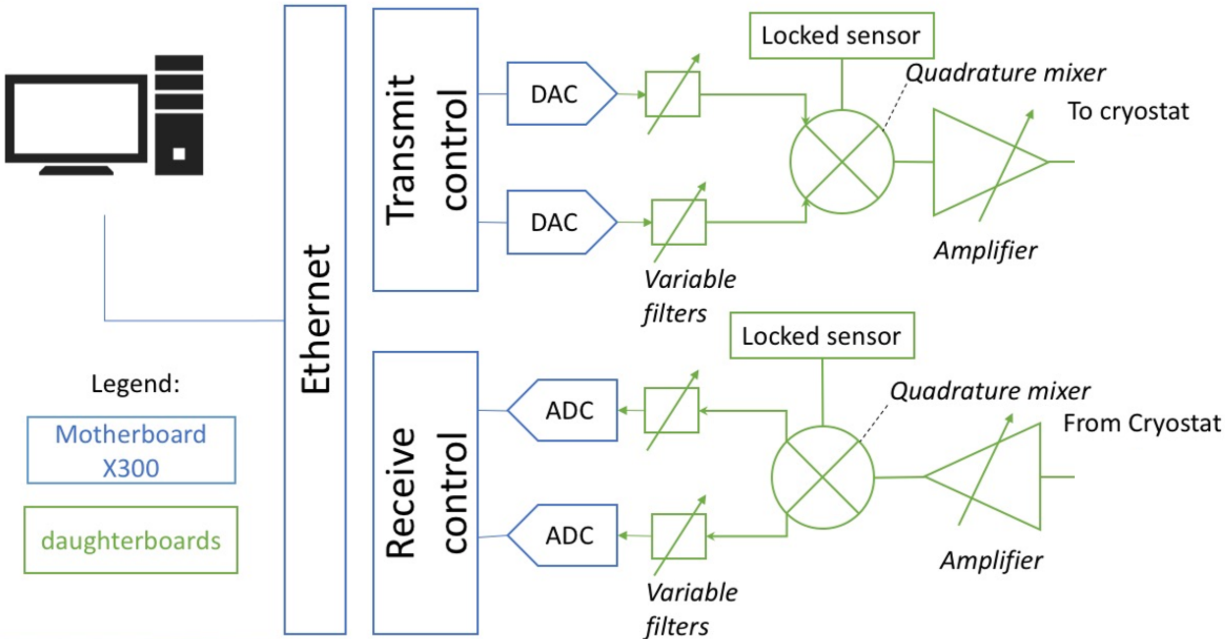
PED134 – NEP all channels



PED134 – signal PSD x optical illumination

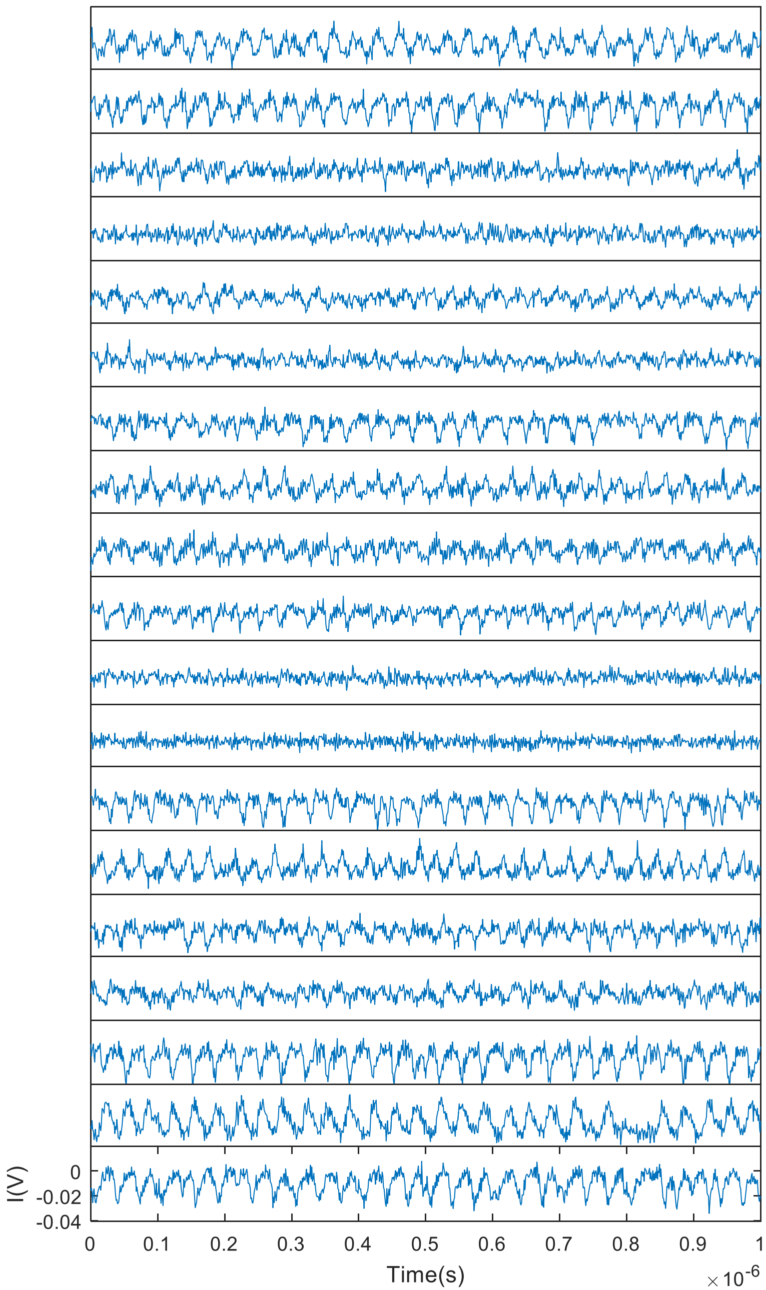


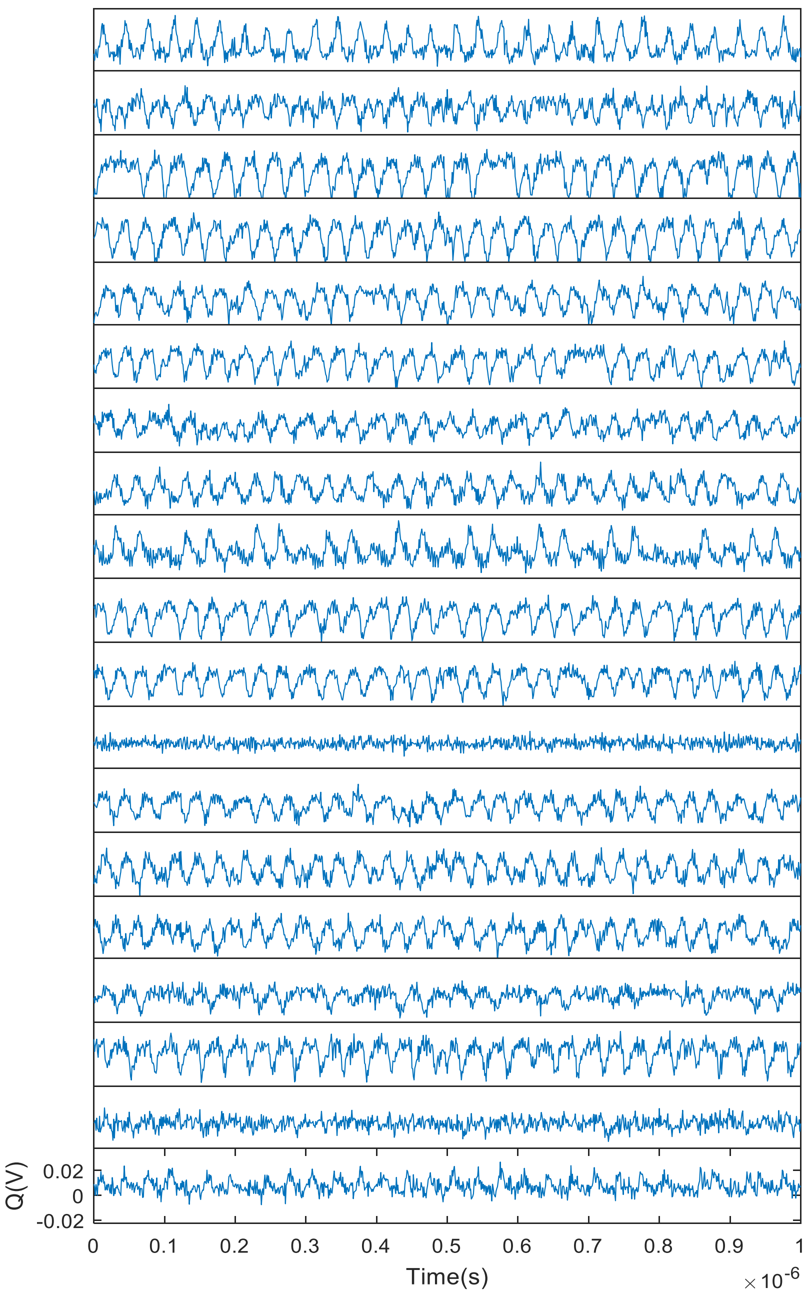
Multiplexed readout X300 USRP – Ettus research



- Uses libraries that are called by python scripts
- 100 MHz bandwidth with current software
- 200 MHz bandwidth with next generation software
- Using two high speed daughterboards will increase bandwidth to 400MHz

19 channels readout simultaneously –PED133





Conclusion

- QCD spectrometer design finalized
- Procurement issued for fabrication (except grating)
- RF multiplexed readout with 100MHz bandwidth demonstrated
- QCD arrays – yield improving
- Need to diagnose and fix efficiency issue

Immersion Grating Spectrometer with Quantum Capacitance Detector Readout

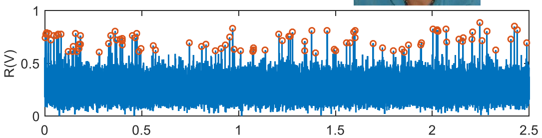
PI: Pierre Echternach - JPL

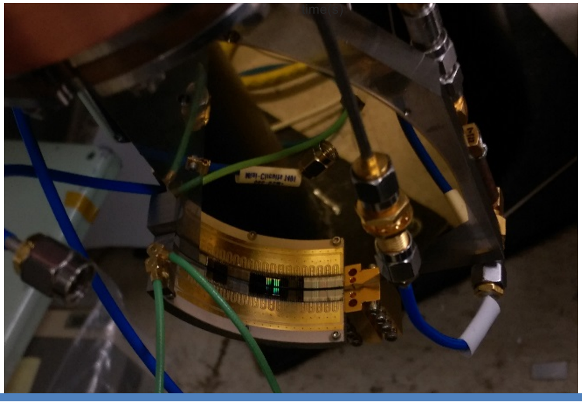
Description and Objectives:

- We are developing an immersion R~ 500 grating spectrometer using a readout based on a novel detector based on superconductor pair-breaking in mesoscopic superconducting devices for the far-IR submm spectral range under very low levels of illumination. We will demonstrate a fully multiplexed 256 spectral channel device with shot noise limited detectors for wavelength between 200 and 350 µm.

Key Challenge/Innovation:

- The key innovation of this device is the combination of a curved grating spectrometer fabricated in silicon and the use of the extreme sensitivity of a quantum system to the external environment as a detection mechanism to build a detector with exquisite sensitivity.





Approach:

- Separate development of wafer spectrometer using characterization by a network analyzer.
- Optimization of stand alone Quantum Capacitance Detectors.
- Development of coupling scheme between spectrometer and QCDs
- Multiplexed readout based on X300 USRP

Key Collaborators:

- C.M. Bradford
- Theodore Reck
- M. Alonso
- D. Hayton
- L. Minutolo
- R. O'Brient

Development Period:

- Oct 2013 -Oct 2017 – no cost extension

Accomplishments and Next Milestones:

- Demonstrated photon shot noise limited performance at 200µm at 0.1aW with 30- 60% end to end efficiency
- Demonstrated first prototype wafer spectrometer R~ 600
- Demonstrated Single Photon detection of 1.5THz radiation
- Redesigned spectrometer with no silicon
- Future milestones
    - Demonstrate free space spectrometer 860GHz to 1.5THz R > 160

Application:

- Future space telescope – SPICA, Origins Space Telescope
- Balloon experiments

*TRLin = **1*** *TRLcurrent = **2*** *TRLtarget = **4***

Far-IR/Submm Array of Multiplexed Single Photon Detectors based on the Quantum Capacitance Detector

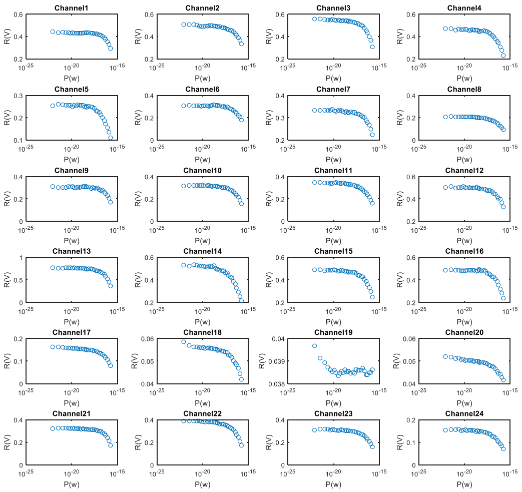
PI: Pierre Echternach - JPL

Description and Objectives:

- We will develop a 500-pixel array of quantum capacitance detectors (QCDs) which have 1) per-pixel noise equivalent power (NEP) below 3×10^{-20} W/sqrt(Hz), 2) high absorption efficiency, and 3) sufficient speed of response to count individual mid-IR through far-IR photons at rates up to 10 kHz. The full array will be read out with a single microwave circuit using a suite of probe tones interacting with resonators

Key Challenge/Innovation:

- The key innovation of this device is the use of the extreme sensitivity an artificial two level quantum system to external perturbation to detect electromagnetic radiation with unprecedented sensitivity and do so in a large array format



Approach:

- Improve yield of current 5x5 pixel design to 100%
- Scale array up to 500 pixels

Key Collaborators:

- C.M. Bradford
- Theodore Reck
- M. Alonso
- D. Hayton
- L. Minutolo
- R. O'Brient

Development Period:

- Oct 2017 -Oct 2021 –

Accomplishments and Next Milestones:

- Improved yield of quantum capacitance signal to 80% on 5x5 array
- Future milestones
  - Improve optical efficiency
  - Scale up array
  - Use X300 USRP to readout large array

Application:

- Future space telescope – SPICA, Origins Space Telescope
- Balloon experiments

TRLin = 1 ***TRLcurrent = 2*** ***TRLtarget = 4***